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A MODEL TO PREDICT FINAL COST GROWTH IN A WEAPON SYSTEM DEVELOPMENT PROGRAM

Anthony S. Babiarz, et al

Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio

August 1975

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The increasing cost growth within the DoD military weapon system acquisition process has been the object of attention for many years. With limited resources and shrinking budgets a viable technique to monitor and control cost growth is needed. The reason for cost growth may be related to the elements of uncertainty within a development program. A conceptual model, previously developed to cope with uncertainties in a weapon system acquisition program, was used to determine its applicability for use in the present study. The model relates the concepts of entropy, information, uncertainty and costs in an effort to predict final costs based on a measure of uncertainty. The measure of uncertainty is entropy, or a lack of order in the information available to the program manager. The model attempts to express final development cost as a ratio of initial cost estimates to program entropy. The study attempts to use subjective, personal probability statements from experts concerning program outcome expectations based on observed data and the total experience of the experts. This study could not, however, verify model applicability based on the assignment of expert subjective probability utilizing the DELPHI procedure. Some other method must be developed to measure outcome probability.

SLSR 49-75B

A MODEL TO PREDICT FINAL COST GROWTH IN A WEAPON SYSTEM DEVELOPMENT PROGRAM

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

Anthony S. Babiarz, BS
Captain, USAF

Peter W. Giedras, BA
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August 1975

id

This thesis, written by

Captain Anthony S. Sabiarz

and

Captain Peter W. Giedras

and approved in an oral examination, has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT

DATE: 13 August 1975

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CHAPTER I

INTRODUCTION

STATEMENT OF THE PROBLEM

Within the Department of Defense (DoD), military weapon system acquisition programs have had a history of substantial cost growth in relationship to the estimated program costs (23). A major factor in such cost growth has been the lack of reliable techniques by which a program manager can formulate cost estimates based both upon available information and the risk and uncertainty involved in predicting future outcomes (4; 5; 16; 18; 23). The program manager is the singularly selected individual chosen by the service secretary to manage and control the development of a major weapon system. He is responsible for the financial, business, and administrative management of the acquisition program. He is charged with planning, directing, and controlling all phases of the weapon system development, production, testing, distribution, and logistic support. It is the program manager who is expected to attain a smooth, integrated effort within and between these phases (21:45). However, without a reliable prediction technique, the program manager's ability to control costs is greatly impeded. A realistic or accurate basis upon which to assess a program's progress and to decide courses of action is absent. A tool, such as a feedback information system and a cost estimating technique, is needed by the program manager to understand and predict the effects of his decisions upon program cost.

SIGNIFICANCE OF THE PROBLEM

Over the years, there has been mounting criticism from both private and Congressional sectors over the increasing costs incurred during the military weapon system acquisition process. Such criticism has particularly emphasized the cost growth of weapon system programs when compared to the estimated program costs (1; 2; 21).

Cost growth is a problem in the weapon system acquisition process (21:43). A review of pertinent literature indicated that the cost growth phenomenon is genuine (1:3; 2; 4; 5). A study conducted by Peck and Scherer (16:1) during the late 1950s reviewed the costs involved in 12 major weapon system acquisition programs. The study found an average cost growth of 220 percent and a standard deviation of 170 percent (23:1) when comparisons to estimated costs were made. During the 1960s, a study conducted by Marschak (16:1) showed an average cost growth of 226 percent for 22 programs. A study accomplished in 1969 revealed that 27 out of the 35 programs reviewed involved cost growths which totaled $19.9 billion (23:1).

BACKGROUND

The phrases, "major weapon system" and "cost growth," are common phrases found in Department of Defense (DoD) procurement related literature. A definition of these phrases should provide the necessary degree of background knowledge to be utilized throughout this study.

Major Weapon System

The phrase, "major weapon system," originated during the post World War II era (16). Prior to World War II, weapons were developed in a piecemeal manner. Increased sophistication and technological advancement led to greater complexity in weapon systems resulting in increased product cost. The phrase, "major weapon system," resulted from a need to distinguish the more costly and complex weapon systems from those essentially less difficult to manage. DoD Directive 5000.1, *Major System Acquisition*, describes a major weapon system in the context of dollar value, national urgency, or recommendations from components within the Department of Defense (32:1).

The phrases, "major weapon system" and "weapon system," in this study will refer to . . .

> . . . the major items used in national defense--costly and technically complex items such as planes, missiles, ships, and tanks. [the phrases cover] . . . not only the major item itself, including onboard subsystems such as power-plant, electronics gear, and armament, but also detached auxiliary facilities and equipment for such purposes as guidance, communication, supply, maintenance, training, and data processing [16:4].

Weapon System Acquisition Process

The process by which weapon systems are acquired by the DoD is termed the weapon system acquisition process (16). The acquisition process is characterized by five distinct, but "overlapping," phases. The phases are called the Conceptual, Validation, Full-Scale Development, Production, and Deployment phases, and are depicted in Figure 1 (16; 17).

Conceptual Phase. The basis for a system program are established in the conceptual phase. Program decisions following this phase determine subsequent system design. The technical, military, and economic basis for an acquisition program are established through comprehensive system studies and experimental hardware development and evaluation. This is a highly iterative phase with activities overlapping rather than occurring sequentially. The activities which usually occur are as follows:

1. Identification and definition of conceptual systems.

2. Analyses (threat, mission feasibility, risk, cost, tradeoff).

3. Design, experimentation, and test of operational requirements, key components, critical subsystems, and marginal technology.

Completion of this phase is marked by a meeting of the Defense System Acquisition Review Council (DSARC). This committee of key DoD officials reviews the program concept for adequate support and determines whether to proceed with or terminate the weapon system development (16; 17).

CONCEPTUAL PHASE		VALIDATION PHASE		FULL-SCALE DEVELOPMENT PHASE		PRODUCTION AND DEPLOYMENT PHASES
Define and select weapon systems concepts which require further development.	D S A R C	Validate and refine performance, cost, and schedule characteristics.	D S A R C	Design, fabricate and test a preproduction system, including all support items which closely approximates the final product.	D S A R C	Efficiently produce and deliver to the operating unit an effective, supportable system at optimum cost.

TIME

Figure 1

Phases of the Weapon System Acquisition Process

Validation Phase. In the validation phase, the major program characteristics (technical, cost, and schedule) are refined and validated through study and analysis, hardware development, or prototype testing. The quantity and level of prototype/hardware validation depends upon the nature of the program, risks, and tradeoffs that are involved, and the suitability of the system definition products. Included in the overall objective of the validation phase are subsidiary objectives to:

1. Provide a basis for contract of commitments prior to source selection.

2. Establish technical interfaces.

3. Define organization and responsibilities.

4. Resolve technical risk areas to the extent feasible.

5. Verify technical approaches.

6. Establish schedules and cost estimates for the full-scale development phase.

7. Establish planning schedules and cost estimates for the production phase.

The validation phase is generally conducted as a DoD-financed effort by two or more contractors working independently in collaboration with the using service under the system program manager's responsibility. The resulting design proposal is considered in the Source-Selection process with the objective of selecting the contractor and the design most likely to successfully complete the weapon system program. Recommendations resulting from the Source-Selection process are considered by the DSARC in light of cost, technical risk, and time. A favorable decision by the DSARC validates the need and design of the weapon system and marks the beginning of the full-scale development phase (16; 17).

Full-Scale Development Phase. There are two basic objectives in the full-scale development phase. The first objective centers around design refinement in terms of financial and technical risks associated with long-term production. "Risk" refers to the possibility of more than one outcome and the objective and/or subjective assignment of a probability of occurrence to each outcome (16:7). (The relationship of risk and uncertainty is discussed later in more detail.) The second objective is to fabricate a working model of the weapon system to test system performance characteristics and manufacturing techniques. This effort is performed under contract by the company selected as a result of the Source Selection process. A DSARC review occurs late in this development phase to review progress. The decision to proceed with production and deployment of the weapon system is made at the time of this DSARC review (16; 17).

Production/Deployment Phases. The last two phases of the acquisition process overlap considerably in terms of time and activity. The production phase is characterized by the production of the system, training equipment, spares, and facilities for operational use. Operational testing and evaluation is conducted on early production items to detect and correct unacceptable deficiencies at the earliest opportunity. The deployment phase begins when production items are provided for use to operational units. The using command begins operational tests on the first unit delivered to determine and improve operational capabilities of the system and to develop the most effective operational tactics, techniques, doctrines, and standards. A formal transition during this phase transfers responsibility from Air Force Systems Command (AFSC) to Air Force Logistics Command (AFLC) for full logistics support and management of the weapon system and related components (16; 17).

Cost Growth

The cost of a weapon system is a major factor in any decision to proceed with development (16:8). Formal weapon system cost estimates fall into three categories: planning estimates; development estimates; and current estimates. Planning estimates are preliminary estimates of total system cost made early in the conceptual phase of acquisition. Development estimates are made near the completion of the validation phase and usually approach the value of the target price of the contract for development. Current estimates are the continual revisions to the estimated final cost of the program (16). Cost growth, in essence, is the positive difference between ultimate, actual cost and the initial estimates (1; 4).

The reasons why initial weapon system cost estimates, or estimates calculated mid-way in the weapon's acquisition life cycle do not reflect the fullest cost possible--and therefore, are not good approximations of later costs--are complex. The reasons are found in the prevailing incentive systems--that combination of rewards, conditions, and constraints which drives individuals to do the things they do (1:2). The reasons are also found in the incentive systems implicit in Government procurement, in military command relationships, and in the industrial marketplace (1:3).

Attention to cost growth has been generated at many levels of government with differing degrees of concern (29). In 1971, the General Accounting Office (GAO) found 61 weapon system programs where costs were approximately 40 percent over the original estimates (2:61). Initially, in order to obtain program authorizations and funding, the program planning estimates had been used by the military departments in their presentations to Congressional committees. The program development estimates, however, were used in subsequent negotiations with contractors (1:5). Of the $23.9 billion difference that the GAO found between the developmental and current estimates, approximately $3.2 billion were attributable to changes in the quantities ordered. In 1972, the GAO found that there was an average expense increase of 31 percent for a total increase of $28 billion for 77 major weapon systems. To combat such cost growths, the DoD has assigned and trained more specialists to strengthen the government in-house capability for making realistic cost estimates (29:23).

At the same time that cost growth has continued and multiplied, there has been a trend for the military forces of the DoD to ". . . cost less than a decade ago in terms of the people, goods, and services taken from the economy [8:16]." Using constant 1974 dollars (8), defense spending for 1974 is $79 billion as compared to $88 billion in 1964. Looking further back, the portion of the federal budget allotted to defense spending has dropped from 60 percent in 1954 to approximately 30 percent in 1974. However, while defense spending has been reduced, total federal spending has doubled (8:10).

The question may therefore be raised, where are federal funds spent? Apparently, the answer lies in the public's demand for more services other than military protection. In the past 10 years, according to Crow (8:10), non-Defense spending has rapidly increased:

> Aid to education has quintupled; public assistance tripled; social security tripled; and health care increased from less than one-half billion dollars to over $18 billion--a more than forty fold increase.

Since both the military structure and spending are decreasing, does this mean that further reductions will eventually eliminate concern over the actual phenomenon of cost growth? In light of the defense policy of the United States, the answer is a definite no. The Secretary of

Defense, The Honorable Mr. James R. Schlesinger (25:4), indicated (in a report to Congress) that past experience has shown that the ". . . long tradition in this country of arming with great haste when war comes upon us, and disarming with even greater haste when the war is over . . . ," is no longer a viable basis for a military defense policy. The costs, in terms of the expenditure of this country's resources, would be too great. Instead, for the foreseeable future, or until such time as world peace and security can be based upon something other than a "balance of arms," the defense policy of the United States will be one of maintaining ". . . a reasonably stable level of defense effort . . . [25:4]." According to Mr. Schlesinger (25:4), this policy means that, at a minimum, this country must:

> . . . keep a visible strategic nuclear balance, contribute to a balance of general purpose forces in Central Europe where the bulk of Soviet and Warsaw Pact forces are arrayed against NATO, and together with our allies maintain a balance of naval forces to ensure the freedom of the seas and the protection of our sea lines of communication . . .

However, to maintain a military force structure within a perceived arms balance requires that the military forces of the United States be modernized at a pace that will keep this country abreast of its potential enemies (25:5). The objective is to maintain a balance of arms in the world and, therefore, relative peace and security. The capability to meet this objective is hindered by the present and continuing need to stabilize the aging process of major weapon systems and their associated components through modernization, which involves the procurement of new systems and the refinement of old systems. However, the cost of acquiring new systems and that of refining existing capabilities is increasing because of inflation and the complexity of the requirements. Unless modernization takes place, the systems and components must either be retired without replacement; replaced on a less than one-to-one basis by more expensive systems and components; or have their service life extended, where possible. To stabilize this aging process and to provide an average age for each weapon system in line with defense policy, recent military studies (25:6) have projected between a $1 billion and $2 billion increase in procurement costs during the period of 1980--1985 just to stop the aging without changing the level of the military forces involved. This estimate does not consider the procurement costs for stopping the aging process of weapon system related equipment. Furthermore, these studies made optimistic assumptions such as: projected force structures will be adequate against future threats; maintenance costs will be constant; and systems acquisition costs, in some areas, may actually decrease (25:7).

In light of the information presented by Mr. Schlesinger (25), the DoD is faced with a dilemma. At the same time that costs are increasing, the DoD budget is constrained. The public's demand for other services from the Government has lead to an expansion of federal spending but, at the same time, the capacity of available resources to fulfill all needs is limited. What funding the DoD does receive must be used judiciously. Since military weapon systems must be developed and procured within existing budget constraints, the historical trend of cost growth for weapon system programs inhibits this judicial expenditure of available funds.

Cost growth needs to be identified and curtailed. Current literature reveals a number of causes for cost growth as shown in Figure 2 (23:88-89). A common thread throughout the literature appears to be the lack of reliable techniques to assess available information in the light of risk and uncertainty in predicting the future, deriving realistic cost estimates, and managing program costs. The lack of reliable techniques and information is presented and discussed by researchers and theorists and is of paramount interest to system program managers (5:116, 124).

The estimates and resulting decisions are a function of available information. When all needed information to select an alternative is known, ". . . there is no reason for a wrong decision . . . [23:37]." However, as the number of alternatives increases, while the available information is incomplete, the resulting estimates or decisions involve varying degrees of uncertainty. The degree of incompleteness increases the risk that a decision will be wrong (16:19-32; 23:37-55).

Preactivation	Activation
1. <u>Cost Estimation</u> a. Cursory cost analysis b. Lack of competition c. Projection & estimating process d. Contractor underpricing	1. <u>Economic Factors</u> a. Inflation b. Order reduction
2. <u>Research and Development Specifications</u> a. Concurrency of research and development with production b. Extraneous design requirements c. Faulty technical planning d. Inadequate task definition	2. <u>Detailed Management Practices</u> a. Lack of cost control b. Inadequate control of sub-contracts c. Excessive reporting requirements
3. <u>External Environment Factors</u> a. Budgetary constraints b. Uncertainty estimation	3. <u>General Management Practices</u> a. Changes in defense procurement policy b. Late delivery of government furnished property c. Program stretch-outs
4. <u>Internal Environment Factors</u> a. Communication problems b. Risk analysis c. The negotiation process	4. <u>Technological Considerations</u> a. Technological obsolescence b. Engineering changes c. Program reduction

Figure 2

Selected Causes of Contract Cost Growth

In effect, the manager is faced with estimates and decisions ranging in a continuous scale from certainty to uncertainty. A degree of risk is incurred when the available information does not provide complete certainty. The more uncertain the outcome, the greater the risk that cost estimates will be in error (16:20-21; 23:37-39). It is apparent that the earlier in the acquisition process that a reliable cost estimating technique can be used, the better the opportunity to control program costs (4:10; 5:4,123-124; 18:2; 25:7).

SCOPE OF THE STUDY

This research study will replicate the Glover-Lenz (16) application of the Martin Cost Model which incorporates uncertainty and cost analysis addressing final weapon system development cost (see Chapter II). The development phase of the F-5E, TIGER II, weapon system acquisition program was the focal point of the research.

Within the realm of full scale development, risk and uncertainty are to be minimized prior to consideration for production and deployment (17). This phase, therefore, was the basis for a study of risk and uncertainty in relationship to the final developmental cost.

In studying this relationship, the Martin Cost Model was used and analyzed as to its capability, as a mathematical model, to integrate the concepts of uncertainty, information, cost, and time into a predictive technique for accurately forecasting the "expected final cost" for the development phase of a weapon system (16). The application of the model was a retrospective attempt to thoroughly consider significant information generated by a recently completed development program.

Glover and Lenz validated the Martin Cost Model by applying historical data from the Short Range Attack Missile (SRAM) development phase. Their conclusion was that:

> The model is a workable method to aid program managers in understanding the potential impact of uncertainty on the final cost of a developmental program [16:42-83].

The present validation considered the negotiated, sole source program of an aircraft weapon system addressing cost growth predictions for the purpose of improving the manager's control of program costs. A conceptual depiction of the procurement process is shown in Figure 3 (16).

OBJECTIVE OF THE STUDY

The primary objective of this study was to test the validity of the Martin Cost Model as a predictor of final weapon system development cost. The cost model was tested using the F-5E, TIGER II, aircraft system development program as opposed to the SRAM missile system development program analyzed in the Glover-Lenz thesis. Secondary purposes are the following:

1. Further develop the Martin Cost Model for program manager use in cost control functions.

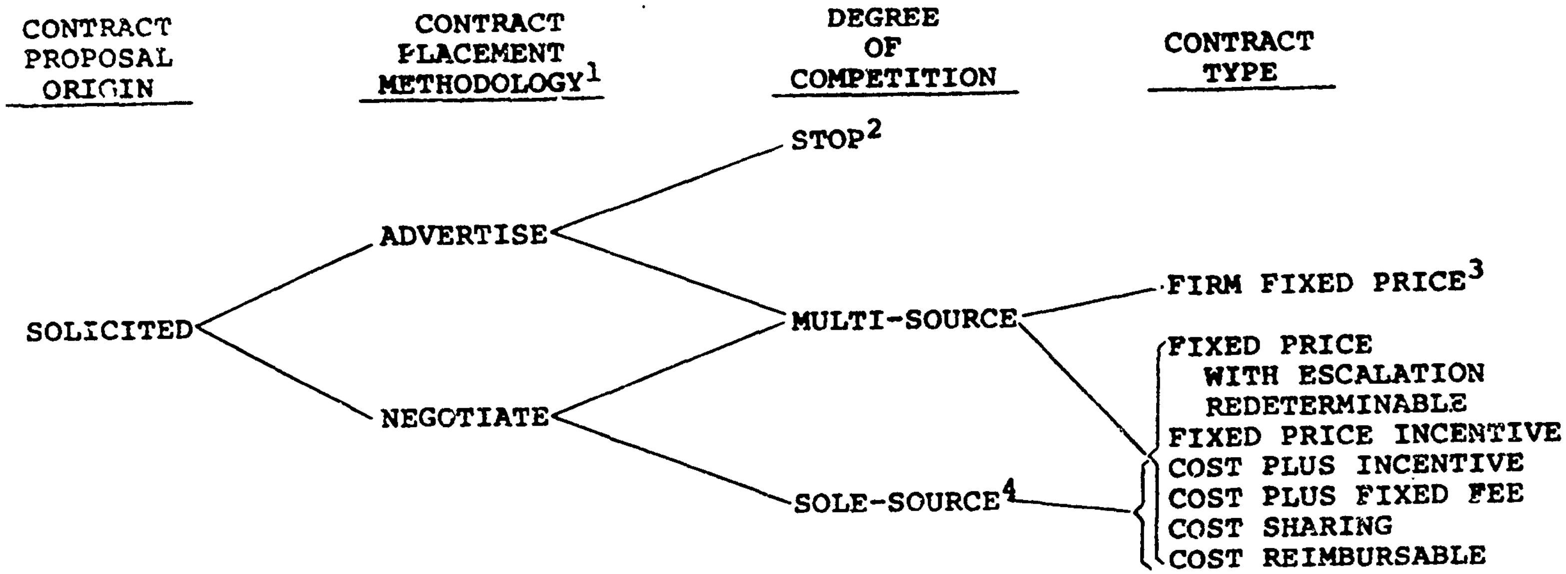

Figure 3

The Procurement Process

Notes:

[1]Placement methodology is governed by U.S. Statute.

[2]Multiple sources are necessary for advertised procurement.

[3]Advertised procurement must result in a Firm Fixed Price Contract.

[4]Weapons acquisition development programs generally fall into this category by virtue of the Source-Selection process.

2. Further develop measures of uncertainty and information in weapon system acquisition.

RESEARCH HYPOTHESIS

The research hypothesis of this report is that there is no difference between the final costs estimated by the Martin Cost Model and the actual costs for a completed weapon system development program.

CHAPTER II

THE MARTIN COST MODEL

In Chapter I, the military weapon system acquisition programs of the Department of Defense (DoD) were described as having a history of substantial cost growth in relationship to the initial estimated program cost. The lack of reliable techniques by which a program manager could formulate accurate cost estimates, based upon available information, was described as a major factor in such cost growth phenomenon. One recently suggested technique for providing the accurate cost estimate required is the Martin Cost Model (16; 23).

The Martin Cost Model does not address all phases of the DoD military weapon system acquisition process. Instead, it was created by Martin as a ". . . conceptual cost model . . . [23:3]," addressing the prediction of final costs for the development phase or subprogram of the acquisition process. The basis for the model is mathematical and involves four conceptual parameters: information, uncertainty, cost, and time. In predicting final costs, the model predicts at the "macro level" of program costs and expresses the prediction ". . . as a mathematical function of uncertainty relative to future events in the . . . [16:19]" development phase.

This chapter will present the derivation of the Martin Cost Model. In the first of three sections, the basic assumption of the model, which equates risk and uncertainty, will be discussed. The second section will present the development of the model within the context of the information system provided for the program manager during the decision-making process. The third section will discuss the model and its application.

RISK AND UNCERTAINTY IN THE DECISION PROCESS

The program manager is part of an on-going organization system that has as its ultimate objective, the successful development of a weapon system within a given budgetary constraint (34:160-164). In achieving that objective, cost estimates are used by the program manager in making decisions that will affect the ultimate cost of the program. As a decision-maker, it is the manager's task to allocate "the available resources of personnel, money, . . . facilities, and material to the various developmental steps . . . [34:163]," within the development phase.

Certainty

A key ingredient for such decision-making is information (15:186-187). If all the information about the outcomes of various selected alternatives is known to the manager, then ". . . there is no reason for a wrong decision . . . [23:37]," to occur. There would be little need for data processing systems, experts, and other agencies to assist the manager in the decision-making process if all outcomes were known. Under complete certainty (the situation in which only one possible outcome can occur as a result of a decision [16:20]), the manager has complete knowledge. The totality of a present situation and all alternatives and resultant outcomes for the future are known.

Risk

As the situation's complexity increases and the number of alternatives multiply, the manager's knowledge about the situation and the alternatives decreases and the information available to the manager decreases (14:7; 15:190-191; 16:19-32; 23:37-55; 34:23,251-267). The degree to which knowledge and information about the present and the future are lacking moves the manager from the area of certainty into that of risk (the possibility that one of several outcomes as a result of a decision may actually occur, each with a specific probability or relative frequency of occurrence [16:20]). The risk incurred is that a selected alternative will not produce the desired outcome at some future time. As that future time becomes further removed from the present, the risk may also increase because the basis for foreseeing the future is incomplete. Thus, the risk of identifying and selecting the wrong alternative, and thereby making the wrong decision, is a function of incomplete knowledge and available information as a result of the time disparity between the present decision situation and the future outcome of the decision.

Uncertainty

In the extreme case, the manager may have complete knowledge and information concerning present events. He does, however, lack virtually all knowledge and information about the future (3:1-89; 4:19-32; 12:9; 14:7,24-25; 15:191; 16:20; 23:37-55). At this extreme, the manager is faced with a situation of total uncertainty. Yet, in the time frame of the present, a decision may still have to be made.

Conceptual Relationship of Certainty, Risk, Uncertainty

It may appear that the authors have made a distinction between the concepts of risk and uncertainty. The distinction would seem to imply that the two concepts cannot be equated. The program manager was described as a decision-maker who is faced with making cost estimates to assist in formulating decisions that will effect the future. Both the costs estimated and the decisions reached are a function of the manager's present knowledge and the information available to him with which to reduce uncertainty. In effect, the manager is faced with integrating his present knowledge using an information system to evaluate the probability of future alternatives. The difference between risk and uncertainty is a matter of degree (15:193; 16:20; 23:38). The concepts of certainty, risk, uncertainty, and time may be graphically represented as shown in Figure 4 (23:Ch.5).

If uncertainty is a total lack of knowledge and information about the future, then, from the standpoint of objective probability measurements (probability derived by specific procedures independent of the problem [23:43]), a relative frequency distribution for the expected outcomes could not be established (3:9; 11:1-3; 15:193; 23:38-39). Certainty would be where an event occurs with a probability of one. As given alternatives are assigned a numerical probability other than one or zero, the situation facing the decision-maker becomes more risky. Risk is the greatest when the probabilities of alternatives are .5 as shown in Figure 5 (23:Ch.5). In terms of objective probabilities, the probability assigned to an alternative is based solely upon the information or data available about the situation. No consideration is given to the decision-maker's prior knowledge and subjective probabilities based on degrees of belief or intuition (23:43).

Frank Knight is credited with maintaining the theory that if uncertainty is measurable, then the degree of uncertainty can be assigned a numerical probability (11:1). Uncertainty becomes, in effect, a degree of risk. If, however, uncertainty cannot be measured and a numerical probability assigned, then real uncertainty exists. The

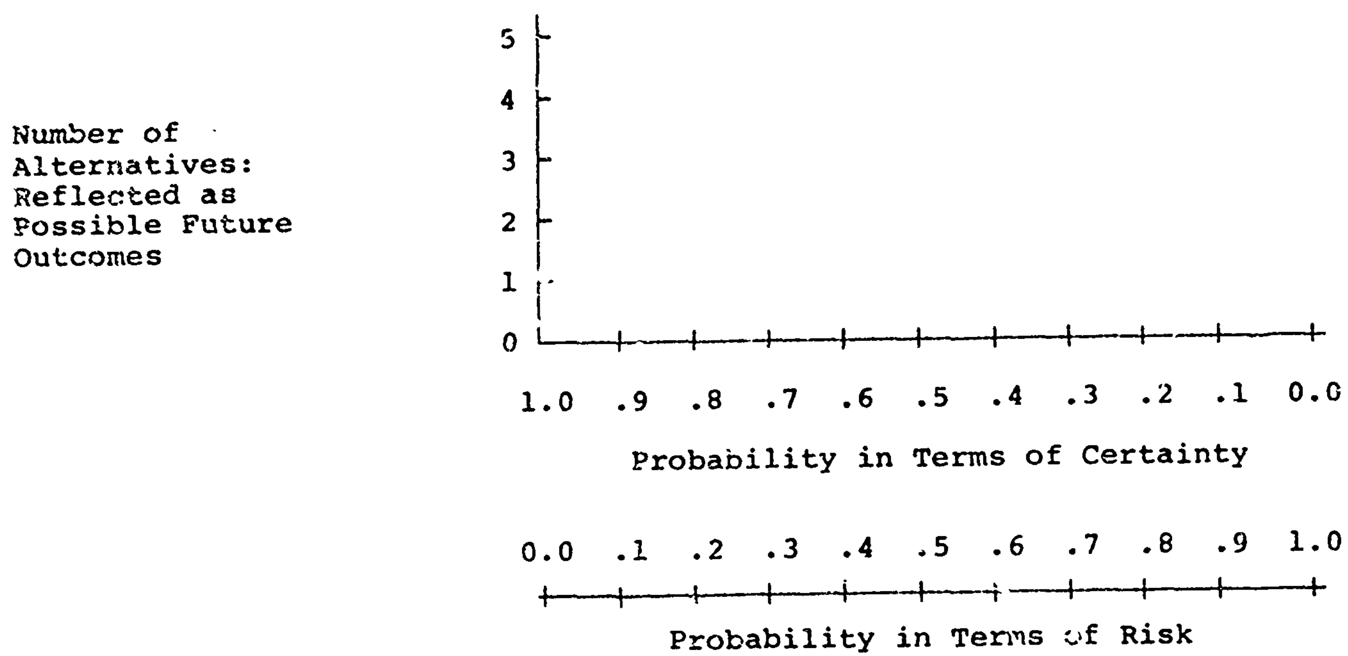

Figure 4

Graphic Representation of a Certainty-Uncertainty Continuum

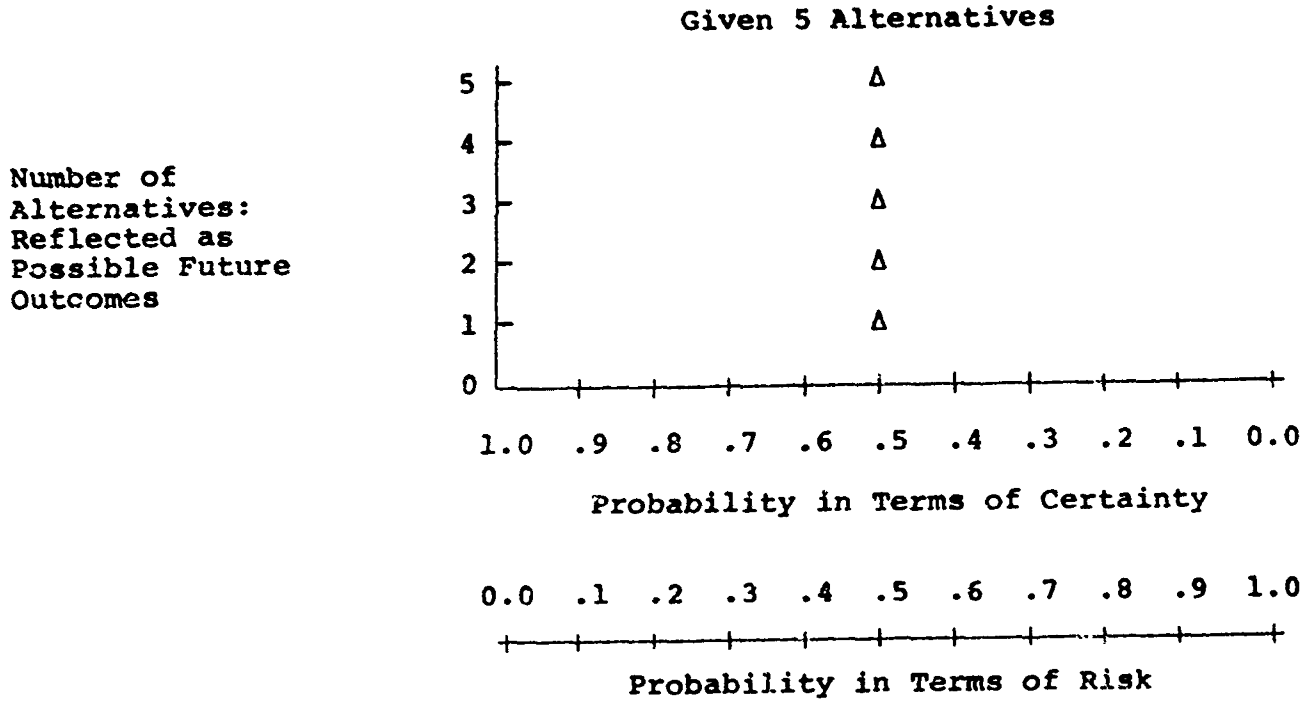

Figure 5

Certainty-Uncertainty Continuum with all Outcomes at a Certainty Probability of Zero and a Risk Probability of One decision-maker would appear to be faced with a situation in which the outcome and, thus, the decision as to the correct course of action, could not be determined. This situation would exist when:

> . . . the decision-maker was ignorant of the statistical frequency of events relevant to his decision; a priori calculations were impossible; the relevant events were in some sense unique; an important once-and-for-all decision was concerned [11:1].

The decision-maker, however, is more than a machine which is fed information and produces a decision (34:163). The decision-maker is a person, an individual. His decisions are tempered not only by the information that he receives but, for example, by his perceptions and background or past experience (15:Ch.6-7). The information he receives is integrated into his existing knowledge, based upon perceived past experience. The cost estimates and decisions made become a product of both objective and subjective probability (3:Ch.2; 11; 16:19-40; 23:37-55). The objective probabilities are numerical values based solely upon the information that the situation provides the decision-maker. The subjective probabilities are constructed from information internal to the decision-maker, based on his past experience. The objective and subjective probabilities are combined to form one frequency distribution for the alternatives identified as shown in Figure 6 (23:Ch.5).

One example of interfacing the objective probability with the subjective is presented by Daniel Ellsberg (11).

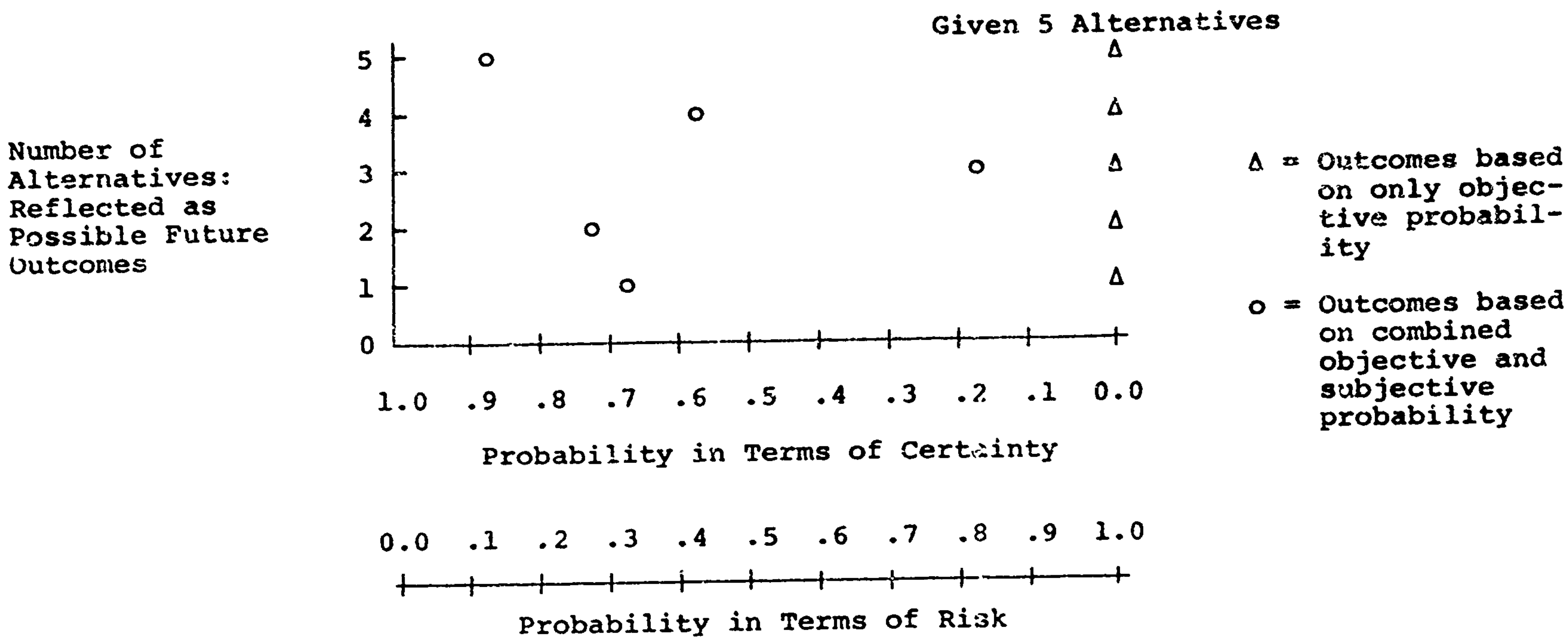

Figure 6

Certainty-Uncertainty Continuum Reflecting a Combination of Objective and Subjective Probabilities

Ellsberg reported that subjects were presented with situations involving varying alternatives or choices with varying probabilities of subsequent occurrence and reward. In each situation, a choice had to be made. Upon interviewing the subjects, it was found that the alternative or choice selected in situations of low or nonexistent objective probability of occurrence involved both the subject's knowledge and the information that he had received. The knowledge or degrees of belief that the individual held were integrated with the information presented to produce a "best estimate" of what was likely to happen.

Ellsberg questions whether or not the decision-maker or the researcher are always able to take qualitative data and convert that data into subjective probability. At least to these authors, there appears to be sufficient techniques available with which to integrate objective probability with subjective probability to produce a single relative frequency distribution (4). The Martin Cost Model and the manipulations previously performed by Glover and Lenz (16) upon the Martin Cost Model appear to have validated the existence of such techniques.

THE MODEL WITHIN AN INFORMATION SYSTEM

As indicated in the previous section, the program manager is part of an on-going organization system that has definite objectives. Within the organizational context, a basic function of the program manager is in the role of decision-maker. As a decision-maker, the program manager is both a receptor for information from outside sources and a source of information himself. To the extent that the outside sources provide complete information about the present and future, the decision-maker can formulate alternatives and arrive at a decision based upon the objective probability of each alternative actually occurring in the future. However, to the extent that outside sources provide incomplete information, the actual occurrence of a given alternative in the future becomes uncertain. Thus, the future outcomes become grouped at the uncertainty end of the certainty-risk-uncertainty continuum. With objective uncertainty, the decision-making process may appear to be nothing more than random selection of an alternative upon which to base a decision. To reduce such uncertainty, the decision-maker augments the provided information with his own past experience. This augmentation involves the combining of objective with subjective probabilities based upon his own past experience and intuition. This combining of the two types of probabilities reduces the grouping of expected outcomes in the area of uncertainty and allows the decision-maker to produce a relative frequency distribution of expected outcomes for the alternatives formulated.

In this section, the program manager, as a decision-maker, is viewed from both the standpoint of a receptor and a source of information. This view necessitates a general discussion of the immediate information system in which the decision-maker operates. It is on this information system, with the decision-maker as both a receptor and a source of information, that the Martin Cost Model is based.

Economic Uncertainty

If the decision-maker had complete information available as to the potential outcomes of selected alternatives, then the decision he made would be made with complete certainty. There would be no risk that a decision was wrong (23:37). When there is complete or perfect information, the situation corresponds to the concept of "pure" or "perfect competition" as defined by the classical school of economics (20:106; 22:205; 23:123). Under perfect competition, the economic situation is characterized as (20:106):

1. Containing markets with ". . . a large number of buyers and sellers of approximately equal importance."

2. Where ". . . the products traded are homogeneous . . ." so that there is no buyer's preference as to a specific product.

3. Where the ". . . buyers and sellers always have full knowledge of the market."

4. Where the ". . . buyers always act rationally and [the] sellers are free to enter and to leave the market at will."

Each of the four characteristics listed above must be present if perfect economic competition is to exist (20:106). Perhaps, at one time, perfect competition did exist. Today, there is little doubt that such competition does not exist (13:34; 20:106). Therefore, the United States

Government, business firms, and industries are interacting in an economic environment that is less than perfect in terms of competition and hence the four characteristics listed above do not apply *in toto*.

This lack of perfect competition clearly appears to be the case in the relationship between the DoD and the DoD weapon systems contractors. As Martin (23:30) has indicated, ". . . the larger number of sole-source negotiated procurements would seem to . . . [characterize a] . . . bilateral monopoly relationship . . ." between the DoD and its contractors. Granted, ". . . at any given time, other economic market classifications may well apply . . . [23:30]," but not under the conditions of perfect competition. In terms of weapon system acquisitions, such factors as the total dollar values involved; Congressional budgetary constraints; changes in technology; advances in research and development; the political climate within this country and the world; and the limited and specialized nature and use of the weapon systems, themselves, tend, at a minimum, to place the DoD in a monopsonistic position and the contractor, as a member of the "defense industry", in a monopolistic position (23:29-36).

Even if the perfect competition characteristics labeled on the previous page as one, two, and four were present, the lack of characteristic number three, full knowledge, would prohibit perfect economic competition. Instead, the lack of full knowledge would create economic uncertainty (16:32). This uncertainty appears evident in the historical trend of cost growth where the actual, final costs of weapon system acquisition programs have deviated widely from the original cost estimates (refer to Chapter I). Furthermore, such factors, as previously mentioned, not only contribute to the general absence of perfect competition characteristics one, two, and four, but also contribute to internal and external economic uncertainties for both the buyer and seller (23:29-36). Internal uncertainties, such as those found in ". . . technical design, . . . [physical] component integration, and financial stability . . ." and the external uncertainties, such as those pertaining to requirements or demands for the procurement of a given weapon system and/or components, may be generated (23:34-35). Possible areas of uncertainty are further exemplified in Table 1 (23:41-43) which presents uncertainty as being grouped under four taxonomic classes.

Since the DoD, in relationship to its weapon system contractors, is interacting in an economic environment of less than perfect competition, there is an element of uncertainty involved in the decision-making process in which the program manager functions. Therefore, sources of information from outside the program manager, himself, may not be sufficient for the formulation of alternatives and the assignment of objective probabilities to future outcomes. Instead, the program manager may have to rely upon an integration of outside sources of information with

Table 1

Uncertainty Taxonomy

Description	Comment
Environmental:	
1a. Nature	1a. The uncertainty is related to natural factors, such as storms and floods.
b. Social and Political	b. The term relates to the impossibility of being able to predict with any precision the actions of social and political groups.
c. Communication Media	c. The disparities that exist in the access which people have to the various informational media. The differences result in ignorance on the part of many groups and individuals.
d. Time	d. The passage of time results in changes which can distort the results of decisions based on a past state-of-affairs.
2a. External	2a. These uncertainties relate to factors external to a project which can impinge on final results.
b. Internal	b. Internal uncertainties comprise those stemming from the technical approach taken, etc.
3a. Exogenous	3a. The stimulus, initiating a given change, comes from outside the organization.
b. Endogenous	b. The stimulus, initiating the change originates within the organization.

Table 1 (continued)

Description	Comment
Functional:	
1a. Business	1a. The firm is uncertain about its future income stream. The risk is associated with the firm's operation.
b. Financial Risk	b. The uncertainty is generated by the ratio of debt to equity in the capital structure. The amount of earnings available to common stockholders. For contracting the risk of profit or loss on an individual contract is involved.
c. Technological Uncertainty	c. Changes in the state-of-the-art can render a weapon obsolete. Thus, uncertainty exists as to how long a weapon can remain in the operational inventory.
d. Production	d. Most products represent an integration of component parts. Should a part not be available, then the finished product cannot be ready on time and even its cost can be affected.
Informational:	
1a. Anticipated Unknowns	1a. The unknowns in this class are those that a contractor is aware of. The problem area is anticipated.
b. Unanticipated Unknowns	b. These unknowns cannot be foreseen.
2a. Known Unknowns	2a. The facts the contractor knows that he does not know.
b. Unknown Unknowns	b. The unknowns the contractor does not anticipate.

Table 1 (continued)

Description	Comment
Technical:	
1a. Uncertainty	1a. The known is completely dominated by the unknown. The probability distributions for future events are not known.
b. Risk	b. A decision leads to one of a specific number of well defined alternatives. The totality of outcomes for a given variable can be described by a probability distribution.
c. Certainty	c. Each decision leads to a predictable outcome. No doubt as to the final outcome is possible.
2a. Subjective	2a. The term relates to the probabilities assigned to an event and which are wholly based on the observation choice.
b. Objective	b. These probabilities are derived by specific procedures independent of the problem being confronted.

his past experience and intuition to arrive at alternatives, assign probabilities to each alternative's future outcome, and render a decision.

The interaction of the program manager as a decision-maker and as a receptor of information from outside sources implies that there exists some type of information system in which the manager functions. This information system shall be discussed next followed by a discussion of the Martin Cost Model.

Information System

As previously indicated, a basic function of the program manager is that of a decision-maker within an on-going organization system. Part of that organization system is the information subsystem in which the program manager functions as a decision-maker (23:118-120).

The information subsystem of the program manager is depicted in Figure 7 (23:119). The subsystem ". . . embodies features of Shannon's communication system and closedloop feedback mechanism of Wiener's cybernetic theory [16:31]." Although the subsystem portrayed may seem simplistic in nature, the subsystem, as a model of the decision-maker's environment, will suffice for developing the underlying concepts and issues of the Martin Cost Model (16:Ch.II; 23:Ch.IX; 28:33-35).

The model in Figure 7 is a closed system relative to the decision-maker and his immediate environment (23:118).

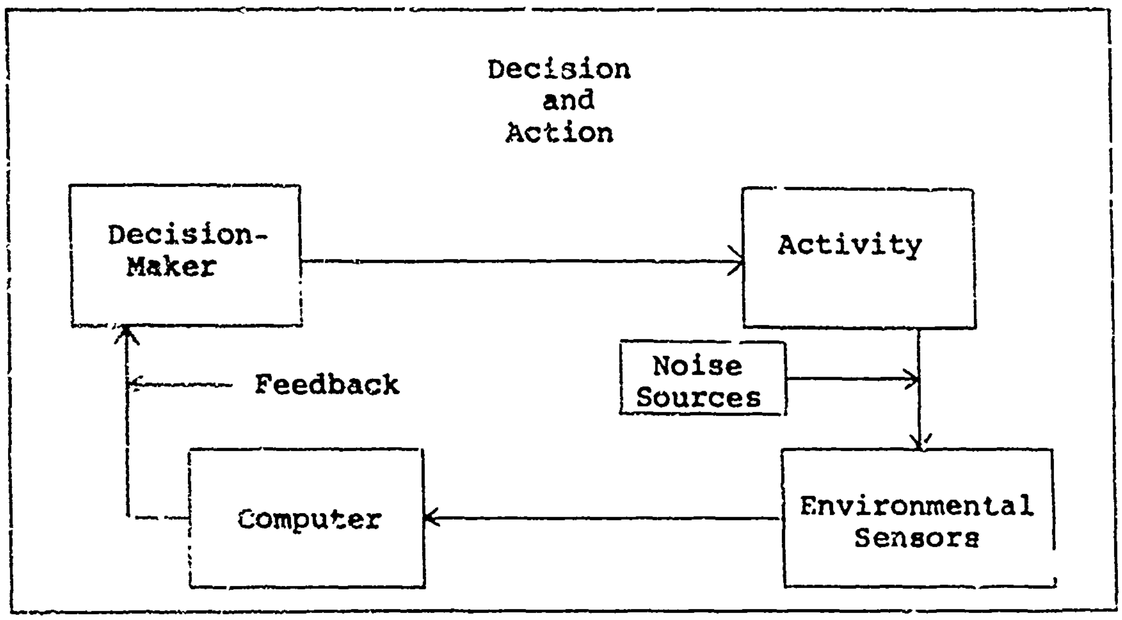

Figure 7

Contract Administration System

In viewing the model, emphasis should be placed upon the receipt of information by the decision-maker rather than upon the transmission of information (23:119). Under such a view, information is considered an input into the information system for the purpose of giving the decision-maker ". . . feedback about the state of [his] . . . [environment] . . . and the financial status of expenditures under a development contract [23:47]." Such information is, therefore, germane to the developmental phase of a given weapon system acquisition program and forms the basis upon which cost estimates for the phase are to be derived. The information can be considered as a "commodity" (23:47) which ". . . add[s] to a representation of what is known, believed, or alleged to be so [34:22]." Thus, information has the potential of increasing knowledge (34:22). The term information can be further delimited by the concepts of amount and usefulness. These two concepts will be explored in subsequent paragraphs. The immediate point, however, is that for the purpose of the Martin Cost Model it is not necessary to expound upon a strict, detailed definition of what information is (23:45). The primary concern is the amount and usefulness of the input information regardless of the form of that information or the means by which that information is transmitted.

If the purpose of the information subsystem is to provide the decision-maker with information in the form of feedback, then a logical place from which to initiate further discussion of the model is the activity node in Figure 7 (16:Ch.II; 23:Ch.IX; 28:33-35). In the most general of terms, the activity node represents the entire environment of the development phase external to the decision-maker. The activity node is the outside source of information for the decision-maker. This node includes, and is focused upon, the activities of both the contractors, who are working upon the development of a weapon system, and the administration of the development contracts (16:32; 23:119-120).

As time passes, the activity node generates information about the implementation and progress of the development phase. This information is gathered and, to varying degrees, collated by the environmental sensors node. The sensors include both civilian and DoD personnel and the various reporting subsystems used in data collection. These sensors also include the manipulation of the information collected into forms that are acceptable for computer processing (28).

Once the information has been collected and processed through the computer node, the decision-maker has information products that provide feedback to him. Feedback not only indicates the current and/or projected state of the development phase, but also gives an indication of how his past decisions have affected the progress of activities. This feedback, in turn, forms the basis for formulating new alternatives and the modification of prior and/or the generation of new decisions. These subsequent decisions are then passed on to the activity node to further circumscribe the content of the activities to be performed.

Noise. Discussion about the model is now complete except for one node, that of noise sources. Within communication theory, noise refers to "distortion," "error," or "extraneous material" being added to the message (28:19; 34:26). Noise could result from such factors as ". . . cursory cost analysis, contractor underpricing, extraneous design requirements, technical changes, . . . inadequate task definition . . . [23:127-128]," or errors and distortion due to incorrect keypunching and reporting. The message which is being transmitted from the activity node to the environmental sensors is a ". . . set of signs . . . [or symbols] . . . that are intended to convey information . . . [34:24]" to a receptor which, in this case, is ultimately the decision-maker. In effect, during the transmittal and receipt processes, noise may be introduced (28:34). This added information, in the form of distortion, error, or extraneous material, obscures, to a certain degree, the original information (34:26). This noise and the original information that the message was to convey cannot be completely separated. Therefore, the final receptor, i.e., the decision-maker, is faced with greater latitude in interpreting the content of the message. As shall shortly be seen, this latitude in interpretation tends to increase the decision-maker's uncertainty as to the exact meaning of the information provided in the message.

To expand upon the concept of noise and to properly relate this concept to the decision-making process within an information system, requires a further explanation of what is meant by the term information. Based upon development of Shannon's presentation (16:Ch.II; 23:Ch.IX; 28:8-16, 100-103), information can be considered to be the number (amount) of alternatives or choices that are available to the receptor for selecting and interpreting a message. Since each interpretation would convey information that was somewhat different from what the original message intended, the receptor is, in effect, confronted with a number of messages, each with a meaning that varies from the other. Thus, the extent to which noise affects the message originating at the activity node, the amount of information, or the number of alternatives or outcomes presented to the receptor are compounded. However, the issue is not the meaning of the information contained in each message, but rather the amount of information presented as represented by the totality of the situation confronting the receptor.

Information, in terms of amount rather than meaning, is exemplified by the following situation. Consider a simplistic situation in which the activity node has generated one message. This message is affected by noise prior to being processed by the environmental sensors. As a result of noise, the decision-maker (the ultimate receptor) is presented with two "alternative messages" from which to choose. Somewhat the same situation was presented by Shannon (26:9) who went on to elaborate as follows:

> To be somewhat more definite, the amount of information is defined, in the simplest cases, to be measured by the logarithm of the number of available choices. It being convenient to use logarithms to the base 2, rather than common or Briggs' logarithm to the base 10, the information, when there are only two choices, is proportional to the logarithm of 2 to the base 2. But this is unity; so that a two-choice situation is characterized by information of unity, ... This unit of information is called a "bit," this word, first suggested by John W. Tukey, being a condensation of "binary digit." When numbers are expressed in the binary system there are only two digits, namely 0 and 1, just as ten digits, 0 to 9 inclusive, are used in the decimal number system which employs 10 as a base. Zero and one may be taken symbolically to represent any two choices, as noted above; so the "binary digit" or "bit" is naturally to associate with the two-choice situation which has unit information.

Consider a situation in which the receptor is confronted with 32 alternative messages (28:9-10). The choice as to which message the receptor should select is equally likely. Using logarithms to the base 2, the situation contains a total amounting to five bits of information. The five bits were derived from the calculation $\log_2 32 = 5$ since $2^5 = 32$.

Entropy. To further measure the amount of information presented to the receptor or the amount of information within the system over time, both Martin and communication theory have borrowed the concept of entropy from the physical sciences (16:21-30; 23:121-123; 28:12-16,19-22,100-103; 34:23,257-265). The concept of entropy was derived from thermodynamics. Entropy is a measure of the "disorder" or the ". . . improbability of the next state . . . [34:21]" of a closed system (23:121). What is measured is ". . . the degree of randomness . . ." within the situation (28:12). Over time, in accordance with the second law of thermodynamics, the tendency is for entropy to increase. Therefore, the system presents an increasing amount of disorder or lack of organization with respect to the amount of information provided the decision-maker. As the number of messages confronting the decision-maker increases, the probability of selecting one message over another as the alternative upon which to base a decision decreases. The situation eventually may become one in which all alternatives appear to the decision-maker as equally likely in probable outcome. Such a situation is one of complete uncertainty as to the future. The relationship between entropy and uncertainty is direct (23:122).

Measurement of Entropy

The measurement of the amount of information presented to the decision-maker is based upon calculating entropy as a ". . . function of probability . . . [16:26]." As described by Glover and Lenz (16:26), the term probability:

> . . . refers to the relative frequency of occurrence of an outcome in a series of trials. [In subsequent examples of entropy calculations, it shall be emphasized that the probabilities referred to are based upon the decision-maker's use of objective and/or subjective probability techniques applied to the alternatives

> presented (16:27).] In the Martin Cost Model, the occurrence of a given cost is considered as [an] outcome. Each alternative choice available to the decision-maker may be expressed as a dollar-cost outcome. The measure of the amount of information, entropy, is a function of the probability of a given outcome, or in the program system, [i.e., development phase], the cost outcome prescribed by a choice of an alternative. Where the number of alternatives increased, the measure of entropy increased.

In calculating entropy, theoretically, the messages presented to the decision-maker might be considered as ". . . continuously variable functions of time . . . [which] can assume an infinite number of bits for exact specifications [34:260]." Under such a consideration, entropy, which is presented by the symbol H, would be expressed as:

$$H = -\int_{-\infty}^{+\infty} p(x) \log p(x) dx$$

which represents ". . . the entropy of a continuous distribution with the density distribution in a function space p(x) . . . [34:260]."

However, in "practical situations," messages cannot ". . . require an infinite frequency band for adequate transmission and interpretation [34:260]." Therefore, entropy, H, calculations can be reduced to a discrete set of probabilities and expressed as:

$$H = -K \sum_{i=1}^{n} p_i \log p_i$$

where p_i represents the probability of a given outcome, n is the total number of outcomes presented, and K is a positive constant and scaling factor (28:87; 34:257).

Since K in the above expression is a scaling factor affecting only the absolute value of H, K can be deleted (16:26; 26:167-168). This deletion reduces the entropy calculation to:

$$H = - \sum_{i=1}^{n} p_i \log p_i$$

In the above mathematical expressions, entropy, H, reflects the total amount of uncertainty present and available in the information system. This total amount reflects the uncertainty confronting the decision-maker in the decision-making process. Uncertainty, i.e., entropy, reaches its maximum when the probability of each alternative's outcome is equally likely (28:15). The probability distribution for the possible outcomes is flat (26:171). Where the probability distribution is not flat, the probability of each outcome occurring is not equal. As the inequality of the probabilities increases, the outcomes spread out and away from the central value (26:170). Thus, entropy can be further viewed and interpreted as a measure of how flat the probability distribution is and represents, in a single value, H, the total amount of uncertainty contained in the system (26:170). As such, it also reflects the variance ". . . about . . . [the] . . . most probable outcome [16:26]." If all outcomes were equally likely, then disorder, as defined by entropy, is complete.

The mathematical expression for H can be transformed into the following ratio (16:29; 28:13; 34:258):

$$h = \frac{-\sum_{i=0}^{n} p_i \log p_i}{H_{max}} \text{ and } H_{max} = \log n$$

where H_{max} represents maximum entropy and h represents the relative entropy of the system. At unity or complete disorder, h=1. For no disorder (complete order or certainty), h=0. Therefore, the range of values for h can be expressed as: $0 \leq h \leq 1$. For example, if h were calculated and found to be .60, then the relative entropy in the system is about 60 percent (28:13).

Negentropy

From a logical standpoint, if entropy reflects the disorder contained in the system, then the opposite of entropy or disorder would be order. The degree of order in the system can be expressed as (16:30):

$$IE = 1 - h$$

where 1 represents unity within the system, h represents relative entropy, and IE represents order. Order in communications theory is referred to as negentropy. If h were .60 as in the above example, then negentropy would be .40. In this situation, there is 40 percent as much information as would exist under certainty. Together, relative entropy and negentropy must equal system unity or 1, i.e., IE + h = 1 in the above expression (16:30).

The amount of negentropy, IE, in the system, represents more than just order (23:120-123). To the extent that there is order, there is certainty. As the amount of order in a system increases, the probability distribution for the outcomes loses its flatness. The probabilities are spread out and are less bunched or grouped together. The probability for each outcome becomes increasingly distinctive in comparison to the other outcomes. Increased order within the system allows the decision-maker to discern differences between the alternative outcomes. The differences are in terms of the probability of future occurrence for each outcome. The uncertainty in selecting an outcome upon which to base a decision is reduced. Certainty is increased and the risk of a wrong decision is lowered. The information contained in the messages becomes more meaningful and, thus, more useful in making a decision. Therefore, the degree of negentropy provided in the system is not only a measure of the order within the system, but also a measure of information content with respect to the meaning and usefulness that the messages provide in reaching a decision.

Informational Efficacy. To emphasize that negentropy not only represents the order or certainty within the system, but also the degree of meaning and usefulness the messages provide, Martin denotes negentropy as IE (23:120-121). IE refers to the informational efficacy of the system and encompasses the total content (order/certainty and meaning/usefulness) of the messages provided as measured by negentropy.

Example of Calculation. Consider the following example of entropy and informational efficacy calculations (23:124). The information subsystem has provided the program manager with five alternatives. Each alternative is a cost estimate of program costs. Since the economic environment is characterized by imperfect competition, there may be a degree of uncertainty associated with the cost estimates. In this particular situation, there is uncertainty and the program manager has had to use both objective and subjective probability techniques to assign a probability of future occurrence to each alternative outcome or cost estimate. The cost estimates and their probabilities are shown in Table 2a.

Given the five alternatives and their associated cost estimates and probabilities, an expected or most probable cost in implementing the program activity can be calculated. Table 2a can now be expanded to reflect the expected value as shown in Table 2b. The expected value is not a cost estimate taken directly from the information provided to the program manager. Instead, the expected

Table 2a

Probability Distribution Table

Alternative Number	Cost Estimate In $ Millions	Probability
1	200	.15
2	350	.25
3	700	.20
4	450	.15
5	800	.25
		1.00

Table 2b

Probability Distribution and Expected Value
(Where n = 5)

Alternative Number	X or Cost Estimate In & Millions	p(x) or Probability	$\sum_{x=1}^{n} xp(x)$ or Expected Value
1	200	.15	30.0
2	350	.25	87.5
3	700	.20	140.0
4	450	.15	67.5
5	800	.25	200.0
		1.00	525.0

value or cost is a weighted average of what the program costs should be in light of the uncertainty that a given outcome will actually occur (26:28-29).

The entropy or degree of uncertainty associated with the above probability distribution of cost estimates is represented in Table 3. The relative entropy and informational efficacy are presented in Table 4.

As can be seen from Table 4, the situation confronting the program manager is extremely uncertain (h=.9843). The alternatives presented are of little meaning or use (IE=.0157) in making the decision. As time passes, the final costs actually involved may deviate greatly from the expected cost (525 [see Table 2b]) or best estimate of what the costs should be in light of the uncertainty involved. From the background provided in Chapter I, the form that the deviation would be expected to take is in terms of a significant cost growth.

Table 5 depicts a situation in which entropy is lower and the informational efficacy is higher than the previous example.

In comparing the values presented in Table 5 with those presented in Tables 3 and 4, it can be seen that the maximum entropy has remained the same since there are still five alternatives confronting the program manager. However, Table 5 reflects a decrease in the entropy and relative entropy values by approximately .28 while informational efficacy has increased by approximately .28 in relationship

Table 3

Entropy Calculation

Alternative Number	p or Probability of Outcome	$\sum_{i=1}^{5} p_i \log_{10} p_i$ or Entropy
1	.15	.1236
2	.25	.1505
3	.20	.1398
4	.15	.1236
5	.25	.1505
	1.00	.6880

Table 4

Relative Entropy and Information Efficacy Calculations (Where $n = 5$)

Calculation	Formula	Result
Maximum Entropy	$H_{max} = \log_{10} n$	.6990
Relative Entropy	$h = \frac{-\sum_{i=1}^{n} p_i \log_{10} p_i}{H_{max}}$	.9843
Informational Efficacy	$IE = 1 - h$	.0157

Table 5

Calculations Under Situation of Increased Certainty

Alternative Number	Cost Estimate In $ Millions	Probability of Outcome	Expected Value	Entropy (Using Base 10)	Max Entropy	Relative Entropy	Informational Efficacy
1	200	.05	10.0	.0651			
2	350	.05	17.5	.0651			
3	700	.55	385.0	.1428			
4	450	.30	135.0	.1569			
5	800	.05	40.0	.0651			
		1.00	587.5	.4950	.6990	.7082	.2918

to system unity or one. Furthermore, the probabilities presented in Table 5 are different from those presented in Table 3. As shown in Figure 8, the probabilities of the alternatives presented in Table 5 have pronounced peaks or are less flat than the probabilities in Table 3. In Figure 8, the individual probabilities are less bunched or grouped together. Both Table 5 and Figure 8 reflect that alternatives number 3 and 4 appear to be much more likely to occur in the future than do the other alternatives. What has happened is that the informational efficacy of the information subsystem has been increased, thereby presenting more meaningful or useful information to the program manager. This increased meaning or usefulness of the information provided has allowed the program manager a greater capability in distinguishing between alternative outcomes. The greater capability is reflected in the probabilities assigned and in the measurement of informational efficacy as presented in Table 5.

The Martin Cost Model

In Chapter I, it was indicated that more accurate program cost estimates are required if available resources are to be used judiciously and the cost growth phenomenon curtailed. However, as already noted, the weapon system acquisition programs exist in an economic environment of imperfect competition. Various factors operating within that environment may render the situation for a given

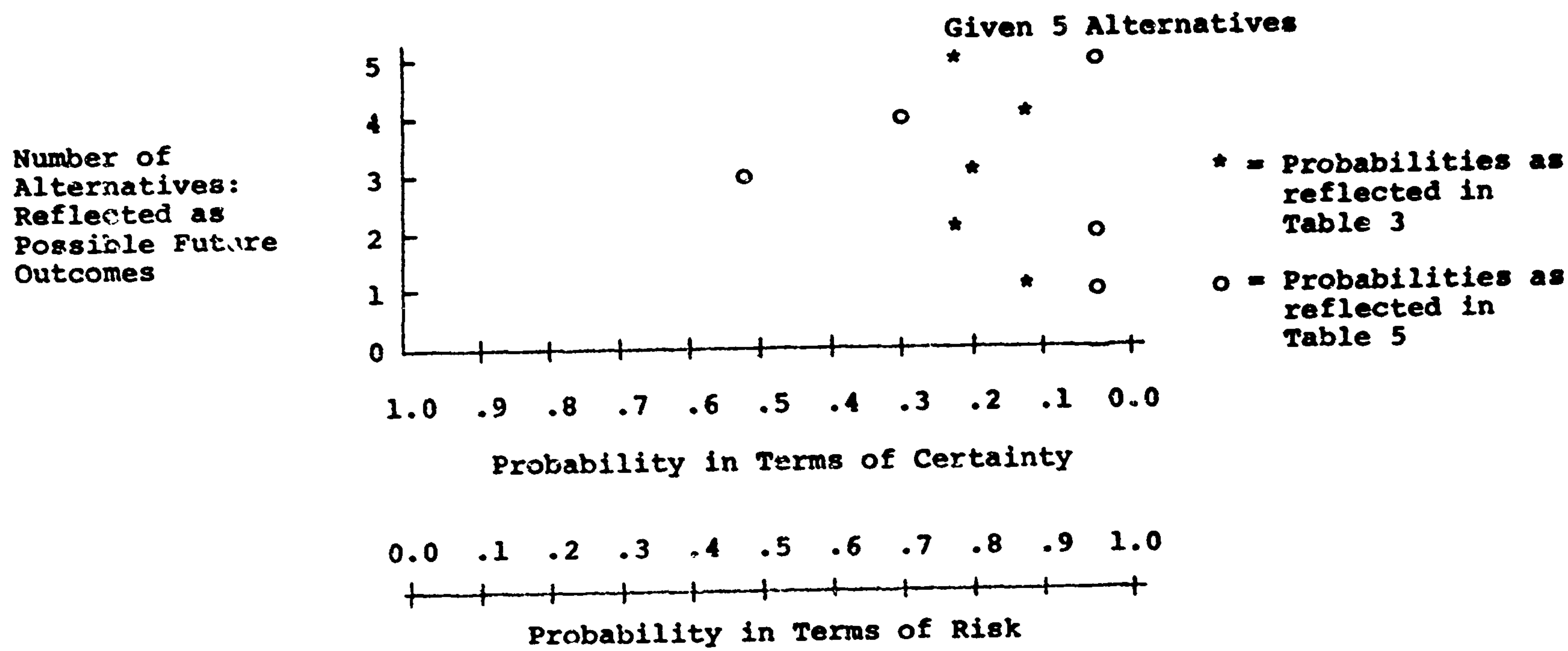

Figure 8

Two Probability Distributions of Five Alternatives development program highly uncertain in terms of final costs. It is possible that informational efficacy could be increased to the point where the costs were accurate within a given situation. The funds required, however, may make the attempt at increasing informational efficacy to the needed level prohibitive (23:130-132). Furthermore, since there is imperfect competition, the degree of informational efficacy required to provide sufficient certainty for accurate cost estimates may not be physically obtainable from the environment. Therefore, at best, it would appear to the authors of this study that the discussion presented so far, if implemented in a development program, would only provide the program manager with the following:

1. A measure of the degree of entropy and informational efficacy or uncertainty/certainty involved in the situation.

2. A probability distribution of alternative cost outcomes and an expected value which represent less useful and meaningful information as entropy increases.

To the degree that entropy exists, the program manager is still left in a position of not knowing what the final program costs will be until the program is completed. Based upon the cost estimates generated, which may have very low probabilities of actual occurrence, how far should the actual costs incurred rise above the estimates before possible cost growths attributable to less than the judicial use of resources are indicated and corrective management actions are taken to reduce such growths?

In an attempt to provide a management tool with which to curtail and control cost growth within a development program, Martin has formulated a mathematical model which integrates the concepts of uncertainty, informational efficacy, costs, and time into a predicative technique not only concerned with initial cost estimates but with the expected final costs of the program (23:125-130). The basis for the prediction of the final expected cost is the cost estimate or "target price" agreed upon by the DoD and the DoD contractor in relationship to the degree of informational efficacy involved in arriving at that estimate or price (16:34-35). The model is mathematically expressed as follows (16:35; 23:126):

$$C_E = \frac{C_I}{IE}$$

Within this expression, C_E represents the expected final cost of the program. The cost referred to is an economic cost which ". . . includes both the . . . [contractor's] . . . cost and profit [16:32]" under DoD contract. Cost, therefore, refers to the total amount to be paid to the contractor by the DoD (16:32). C_I represents an initial cost estimate or target price, and also refers to the total amount to be paid (16:32). IE represents the informational efficacy involved in the generation of C_I.

For example, consider again the situation presented in Table 5. Suppose that the target price finally agreed upon by the DoD and the contractor was alternative number 3 with a cost of 385 at a probability outcome of .55. Using the Martin Cost Model, C_I would be 385 and IE would be .2918. C_E would thus be calculated to be approximately 1319.4. In this case, C_E represents approximately a 243 percent increase over the initial target price. This increase may suggest to the program manager that more information should be acquired, potential cost growth factors identified, and action taken to preclude this possible 243 percent cost increase.

The above situation is projected through time in Figure 9 (16:37-39). The program is initiated at time T_O with the awarding of the program contract. Time will pass in intervals of T, such as fiscal quarters per year, until the contract is terminated and the program completed in the n^{th} period or T_n. At time T_O, the program manager plotted the expected costs of the program over time based on the expected final cost, C_E, of 1319.4. To plot this line, labeled C_E, it is assumed that there are zero start up costs at time T_O due to the contractor already belonging to the defense industry (16:36). It was further assumed that costs would accumulate over time linearly (16:36). When period T_n becomes the present rather than the future, the actual, final costs will be known. Based upon the research hypothesis of this study, there should be no difference between the expected final costs at T_n derived from the Martin Cost Model using the degree of informational efficacy present at T_O and the actual, final costs.

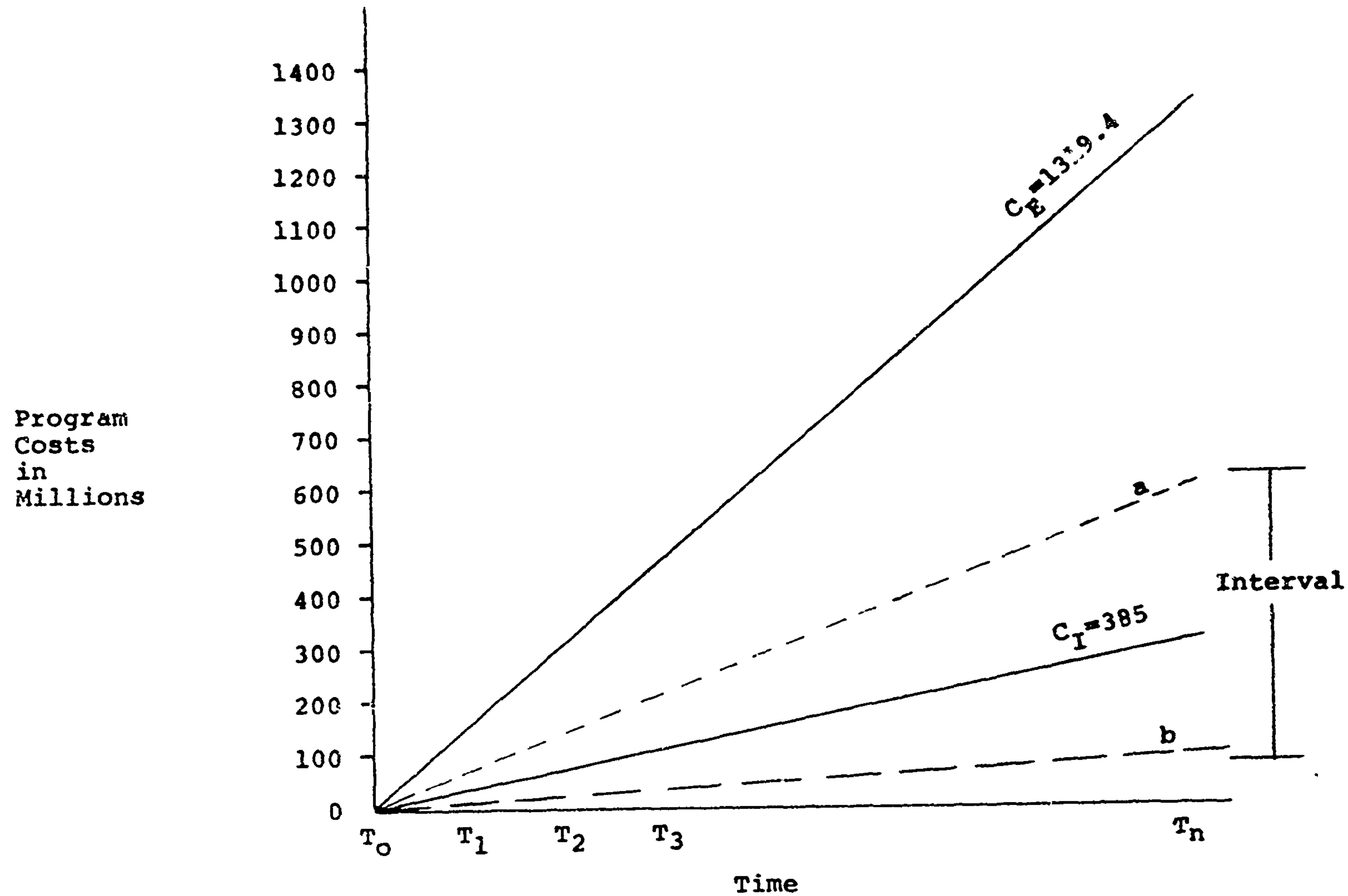

Figure 9

Cost Projection

While at T_O, the program manager also plotted line C_I, over time, based upon the estimated cost or target price of 385. The same assumptions as mentioned for plotting line C_E, were applied. There is a probability of .55 that the target price of 385 will be the actual, final cost at T_n. Since C_I at 385 is the target price at which the contract was awarded, C_I is the cost line that the program manager will monitor. To assist the program manager in monitoring costs, suppose dash lines a and b are established as tolerance levels on either side of the cost line, C_I. As long as the actual costs occurring over time stay within the interval created by the dash lines a and b, the costs of the program are not out of control. However, in this case, cost line C_E immediately deviates beyond the interval a,b after point T_O; an out of control situation potentially exists and cost growth is likely. The program manager, therefore, should take actions which include an analysis of the program in light of the entropy computations made at T_O to determine areas where more information is required, thus reducing uncertainty and regaining control over costs.

So far, the discussion of the use of the Martin Cost Model has been limited to the generation of an expected final cost and a cost estimate or target price based solely upon informational efficacy provided at one point in time. That time is at the initiation of the development program. The economic environment, however, contains uncertainties. In time, these uncertainties could present unexpected events that affect either or both of the cost lines, C_E and C_I (16:78). At the time that the program manager becomes aware of such events and is presented with meaningful and useful information with which to deal with those events, the cost lines, as applicable, could be replotted using the same techniques as have already been described. For example, consider an unexpected technological breakthrough at time interval T_4 which has caused a major revision to the weapon system under development. In this instance, as reflected in Figure 10, both cost lines C_E and C_I were recalculated and replotted along with interval a, b, using the level of informational efficacy provided at T_4. Also, the original C_I and C_E lines, based upon the informational efficacy provided at T_O, are still shown due to the original development contract being under renegotiations.

APPLICATION OF THE MODEL

Review and Significance of the Model

At the end of the previous section to this Chapter, somewhat simplistic applications of the Martin Cost Model were presented in Figures 9 and 10. These examples, however, seem to imply an apparent flexibility and adaptiveness of the model to the passage of time and to a changing

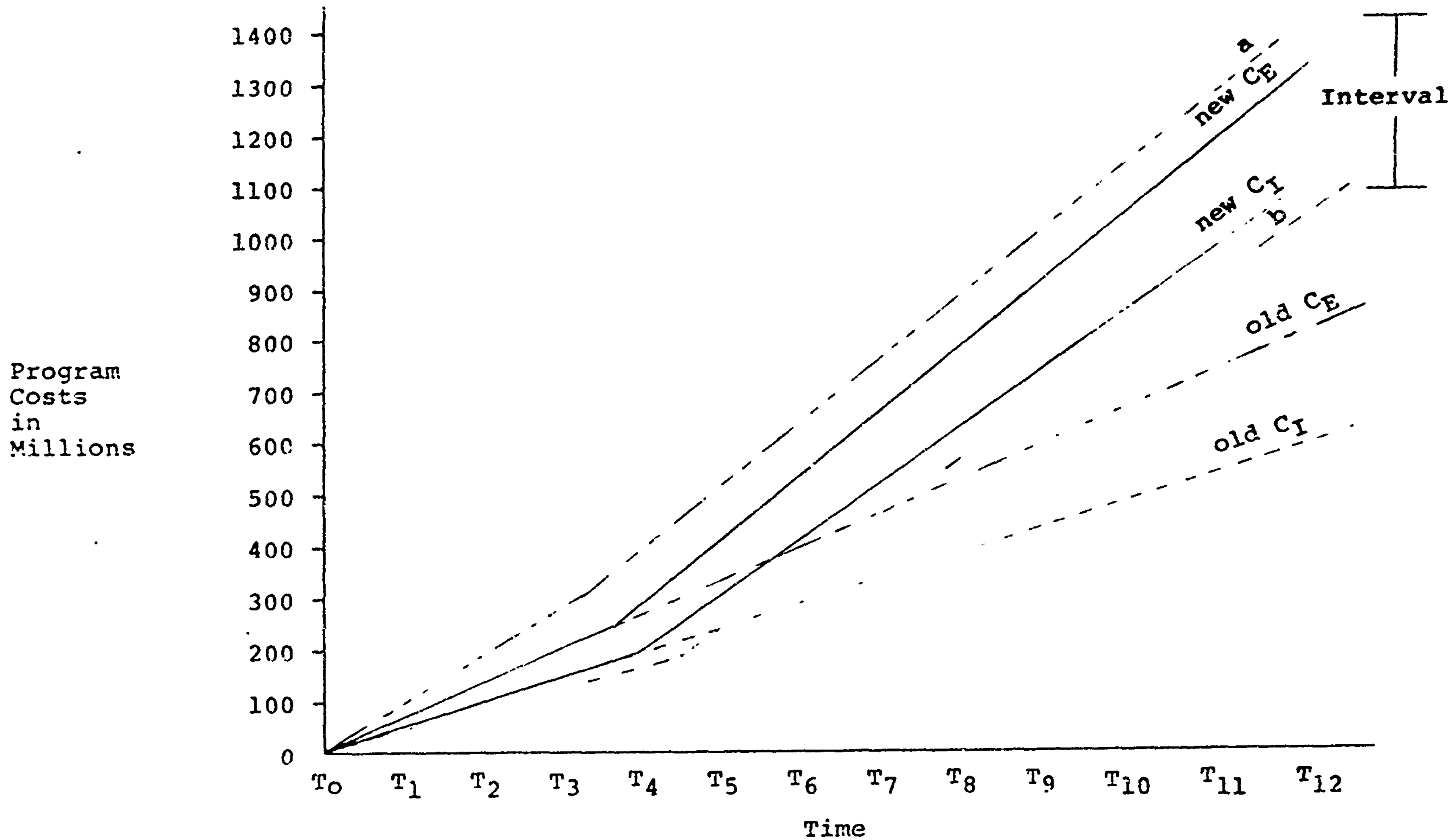

Figure 10

Modified Cost Projection

environment. The underlying continuum for the model is time, from the present, which incorporates the past, and on into the future as far as a given estimate is required to be projected. Further, the model appears to be able to move with time. As the future becomes the present, the model can again be applied from this new point in time.

Within the time continuum, the final expected costs of the program and the alternative cost estimates and target price can be evaluated based upon a second continuum. The second continuum involves the measurement of the certainty and uncertainty or risk associated with making decisions affecting the future based upon the information presently provided. To the extent that the information is meaningful and useful to the decision-maker in differentiating alternatives by probability of occurrence, then the certainty with which a decision can be made is increased and the risk of error reduced. Thus, the emphasis of the model is upon the measurement of the present level of informational efficacy within the decision-maker's information subsystem and the relationship of that informational efficacy to decision-making in terms of the management and control of the future with respect to potential program cost growth (16:3-40; 23:125-129).

Assumptions of the Model

Having presented the conceptual basis for the model and the mathematical techniques required, there are seven major assumptions which can be derived.

1. The conceptual foundation of the model and the predictions generated by the model provide a "descriptive" rather than "normative" basis upon which to analyze cost growth at the macro level of a development program.

2. The expected, final cost of a development program can be formulated based upon the ratio of cost estimate or target price to the level of informational efficacy provided in a closed-looped information subsystem at the time that the estimate or price was established.

3. The economic environment in which weapon system acquisition programs function may reflect perfect economic competition but such competition is deemed highly improbable.

4. The information subsystem of the program manager can be characterized as a closed-loop system which possesses both a time and a certainty-risk-uncertainty continuum. The certainty-risk-uncertainty continuum, in turn, assumes that:

a. Uncertainty can be equated to risk and can be measured by the amount of entropy contained in the information subsystem.

b. Negentropy can be equated to informational efficacy which, in turn, can be measured as the remainder of system unity or one after relative entropy has been subtracted from unity. Informational efficacy further equates to certainty within the information subsystem.

5. Informational efficacy varies inversely with the amount of entropy contained in the information subsystem.

6. All terms reflecting cost or price in the model refer to an economic cost consisting of both the DoD contractor's costs and profits.

7. There are no fund limitations imposed directly upon the Martin Cost Model. If funding limitations exist, the limitations were considered by the information subsystem at the time that cost estimates and target price were formulated as alternatives.

These assumptions are basically the same as the assumptions presented by both Martin (23:125-127) and Glover and Lenz (16:33-34).

Model Limitations

Besides the assumptions listed, the authors of this study believe that there may presently be three basic limitations to the application of the model. First of all, the model was specifically developed for application in the development phase of the weapon acquisition program (23:5). The only known validation attempt for the model, as far as the authors have been able to research, is the study accomplished by Glover and Lenz (16). The Glover and Lenz study also applied to the development phase. Therefore, until such time as further validations are performed to include areas other than the development phase, the application of the model may be restricted to the development phase (16:35-36).

A second limitation appears to be in the alternatives provided by the information subsystem (16:36). If all possible alternatives are not identified by the information subsystem, the measurement of entropy and informational efficacy may be in error. These errors may cause the accuracy of expected, final costs predicted by the model to decrease.

The third limitation is that the Martin Cost Model was formulated as part of a total program cost model.

Within the total cost model (23:125-147), the costs of providing various levels of informational efficacy are considered in conjunction with the basic Martin Cost Model as presented in this study and by Glover and Lenz (16). The Martin Cost Model, itself, could be modified to include such economic variables as inflation. Thus, the results obtained from this study and that of Glover and Lenz may not be indicative of the actual capabilities of the Martin Cost Model if applied as part of the total cost model formulated by Martin.

CONCLUSION

If the basic Martin Cost Model can be sufficiently validated for application within the development phase, then the basic model may form the foundation for predictive and managerial techniques with which to curtail, at least, that portion of the cost growth phenomenon that is amenable to control by the program manager.

CHAPTER III

METHODOLOGY

The research methods applied to this study may be divided into the following general topics:

1. Literature Review
2. Data Collection
3. Data Analysis
4. Data Summary

This chapter will describe the procedures that were used and the results of data collection and analysis of the Martin Cost Model. Chapter IV presents an analysis summary and interpretation of the findings based upon the results of the data collection, data analysis, and test procedures. Chapter V presents concluding remarks and recommendations for future studies.

LITERATURE REVIEW

The purpose of the literature review was to collect information in the following areas:

1. DoD weapon system acquisition process and phases.
2. DoD weapon system costs.
3. Cost growth and cost control techniques.

4. Decision making processes and techniques.

5. Communications and information concepts, theories, and techniques.

6. Statistical methods and application as they are related to decision making.

7. Research data techniques and methodologies.

These seven areas were considered the major areas of concern or relevancy in developing the present study. Although the Martin Cost Model was used in this study, other predictive models were examined during the review. The results of the literature review were presented in Chapters I and II.

While the research methodology used in this study can be divided into four general topical areas, the basis for the detailed expansion of the methodology employed rested upon the results of the literature review and the authors' decision to replicate the study by Glover and Lenz with subsequent use of that study as a guideline for performing the research effort presented here. The remaining sections of this chapter present the details of the data collection and then the statistical and testing procedures used, accompanied by the results obtained by use of those procedures.

DATA COLLECTION

Overview

The collection of data was oriented towards the replication of the Glover and Lenz study of the Martin Cost

Model. The present study attempted to further examine the capability of that model to accurately predict the final development costs of a weapon system. This capability was tested using the data obtained from the F-5E, TIGER II, aircraft weapon system development program. The data obtained was separated into two categories. The first category included the data to be used in determining the entropy or uncertainty that existed at the time of contract award for the aircraft's development. The second category was historical in nature and dealt with the actual costs incurred during the development phase. This cost data was used in performing tests of the cost estimate produced by the model based upon the data provided under the first category.

Variables Within the Study

Both data categories involve consideration of four variables. These variables correspond to the four concepts (uncertainty, informational efficacy, costs, and time) that are integrated by Martin's mathematical model into a cost prediction technique. In the following paragraphs, time and cost will each be discussed separately while informational efficacy and uncertainty will be discussed from the standpoint of entropy.

Time. As presented in Chapter II, time was described as the underlying continuum for the Martin Cost Model. Time consists of the present, which incorporates the past, and the future for as far as a given cost estimate is required to be projected. The passage of time can be depicted as presented on pages 58-60 of Chapter II. Time passes in intervals of T. Each interval was one calendar quarter or three months in duration. Time started at T_o which represents the last day of the calendar quarter in which the development contract was awarded (31 December 1970) and marks the beginning of the development program. The completion of the program is designated by T_n or the last day of the n^{th} quarter (30 June 1974). Calendar quarters between T_o and T_n are represented by T_i, reflecting the last day of the i^{th} quarter.

Cost. In Chapter II, the term cost was discussed. In this study, cost refers to the economic cost of the weapon system's development to include the contractor's profit. As reflected in Table 12, Appendix C (p. 126), the data on the cost of development was obtained and used in analysis by calendar quarters or time intervals of T. However, the cost data presented is cumulative by quarter, with T_n or the 14^{th} time interval reflecting the final cost of the development program. Costs have been rounded to the nearest thousand dollars and are reported in millions of dollars. For example, a figure of $10,112,020 would be reflected as $10.112 million.

The specific notation to be used in conjunction with the cost variable, as shown in Chapter II, is restated below:

$C_I \equiv$ Initial cost estimate or target price at the time that the contract was awarded.

$C_E \equiv$ Expected final cost of the program as predicted by the model.

Added to this notation are the following symbols:

$C_A \equiv$ Actual final cost ($89.322 million).

$C_i \equiv$ Quarterly cumulative cost actually incurred for time interval t_i.

<u>Entropy</u>. The concept of entropy was discussed earlier in Chapter II. The term entropy was equated with the uncertainty confronting the decision-maker in the decision-making process. Entropy reflects the degree of disorder or the lack of organization in the amount of information presented to the decision-maker by his information system and from which he is to select an alternative. In a given situation, this uncertainty or entropy reaches a maximum when the probability of each alternative's outcome actually occurring in the future is considered to be equally likely by the decision-maker. To calculate the relative entropy (h) of a given situation, the following expression is used:

$$h = \frac{-\sum_{i=0}^{n} P_i \log P_i}{\log n} \quad \text{and} \quad \log n = H_{max}$$

where n is the total number of outcomes or alternatives presented in the decision-making situation, P_i represents the probability of a given outcome occurring, and H_{max}

reflects the maximum entropy. The n outcomes are assumed to be collectively exhaustive and mutually exclusive. Further, the probabilities, P_i, are constrained as follows:

1. $0.0 \leq P_i \leq 1.0$

2. $\sum_{i=1}^{n} P_i = 1.0$

Informational efficacy (IE) is the opposite of entropy and reflects both the order within the situation or information system and the degree to which the information provided is meaningful or useful to the decision-maker. As IE increases, certainty increases and the amount of relative entropy, h, decreases. The degree of order and the usefulnesc of the information provided can be expressed by:

$$IE = 1 - h$$

Both of these calculations, h and IE, are critical to the generation of cost predictions by the model. Obviously, to produce meaningful calculations, a data base is required. That base shall be discussed next.

Source of Data

Since a study involving a development program which was just getting underway would have been both beyond the scope and time constraints of the present study, the data base for this study rested upon the selection of a recently completed development program as discussed in Chapter I. The program selected was the F-5E, TIGER II, Aircraft

Development Program. The System Program Office (SPO) for the F-5E is located at Wright-Patterson Air Force Base, Ohio.

Aside from considerations of scope and time, the authors' selection of the F-5E as the data source was based upon the following reasoning:

1. Although the program did not deal with the development of a new weapon system, per se, the program did include major modifications to an aircraft which reflected technological advancements.

2. The desired aircraft modifications were assumed to be sufficiently within the state of the art at the time that the development contract was awarded so as to preclude the generation of almost complete uncertainty while yet avoiding almost complete certainty on all aspects of the development. Thus, it was hoped that the development of the aircraft would not involve an examination of the model at the extremes of the certainty-risk-uncertainty continuum, but, instead, would be more aligned with the situation found by Glover and Lenz in which relative entropy was computed to be 0.686 (16:53).

3. The magnitude of the dollar value involved in the contract, $83,635,000 was considered substantial by the authors and thus would not represent a trivial application of the Martin Cost Model.

4. Both the SPO and data locations were in the proximity of the research center (16:46). This physical closeness was expected to ease the research effort while reducing any costs involved in that effort.

5. Personnel who had been in key managerial positions during the development phase were still located at the SPO.

6. The development phase had only recently been completed (30 June 1974). Data were readily available and the experiences of having worked on the program should still be somewhat fresh in the minds of the key personnel within the SPO.

Specific Sources for Entropy (Uncertainty) and Informational Efficacy. Having selected the F-5E, TIGER II, for the data base, the authors contacted the United States Air Force Business Research Management Office located at Wright-Patterson Air Force Base, Ohio. Through the assistance rendered by the Center, the authors readily gained access to the F-5E SPO Director. The authors obtained approval from the Director to use information about the F-5E development phase for the purposes of this study. At the authors' request, the Director also furnished the names of six personnel (participants) within the SPO whom he believed had been in various managerial positions directly involved during the development of the F-5E. As shall be further discussed in subsequent paragraphs, the authors' selection of a directed interview technique using the DELPHI procedure as a means of data collection necessitated the indentification and involvement of the participants in this study.

Prior to the actual collection of data, the authors contacted each prospective participant to elicit their cooperation in the study, to establish times for the interviews, and to determine whether or not the prospective participant had in fact been in a managerial position directly involved during the development phase. Three of the participants were found to have been involved while three were not involved during the development phase. The three that had not been directly involved were deleted from further consideration within the study. One of the three prospective participants that was removed from the study, however, did provide the authors with the name of a seventh prospective participant. This seventh individual was contacted and was found to have been involved as a manager. The data base was initially to be gathered from four managerial participants. Since anonymity had been promised by the authors during the elicitation of their cooperation, there can be no further description of the participants provided except as follows:

1. Each had been in a managerial position during the development phase. One participant was positioned within the Engineering section of the SPO, another within the Management section, and two within the Financial Management section.

2. Three of the participants had Government Service ratings of 13 at the time while the fourth had been a second lieutenant within the United States Air Force.

3. Three of the participants had been in one or more managerial positions from the on-set of the development phase. The fourth had managerial experience directly related to the program only after the development phase had begun. However, this fourth participant indicated to the authors and to the authors' satisfaction that he was well familiar with the development phase and could provide an adequate source of information.

Although the data base was initially formulated around four participants, one participant in the SPO Management section was subsequently deleted from the study. His removal was due to an unexpected temporary duty assignment to another area of the country. Since the assignment was projected to last from 7 to 14 days, the authors felt that under the DELPHI procedure being used the time delay could have adversely affected the collection of data from all participants (4:62). Therefore, the participant was removed, but the data that had been collected up until the time of his departure was retained within the study and used in conjunction with further data collection from the remaining three participants. For further explanation pertaining to this removal, refer to Appendix A (p. 105).

While the current study is basically a replication of the Glover and Lenz study, the authors assumed that the data base formed by the participants would be sufficient for the purposes of this study. Glover and Lenz had not only collected data from participants using the DELPHI procedure but had also reviewed weapon system program documents including source selection data (16:47). However, such a review was assumed to be unnecessary by the authors, since a detailed analysis of a specific development program is not the intent of the research effort and neither the Martin Cost Model nor the DELPHI procedure appear to require such a review.

Interview and DELPHI Procedure. By virtue of its definition, the data necessary to evaluate entropy was not expected to be found in a single report, document, or individual. The objective was to collect applicable data that was in existence at the time of contract award.

To calculate entropy as formulated in Chapter II, it was necessary to collect data regarding possible program outcomes and the probability of each outcome. To accomplish this collection task, a process used by the RAND Corporation for the elicitation of expert opinion, called the DELPHI procedure, appeared to be suitable for the purpose.

The DELPHI procedure is a method to elicit the opinions of experts (6) using a carefully designed questionnaire administered in a series of iterative rounds of questioning (9) in the form of a directed interview. Associated with each round of questioning is a feedback of information gathered from the previous round (10). The feedback and the subsequent data gathered is refined in each successive iteration (7).

The DELPHI procedure has certain desirable advantages (19:20-23):

1. Concensus reflects reasoned, self-aware subjective valuations expressed in the light of subjective evaluations of associate experts.

2. Controlled feedback makes group estimates more accurate.

3. Procedures create a well-defined process that can be described quantitatively.

The DELPHI procedure is an alternative to the committee approach for eliciting a group judgment. It improves upon the committee approach by subjecting individual expert views to criticism without face-to-face confrontation. It provides anonymity of opinion (4:44). Thus, it attempts to improve upon the committee approach by allowing the exchange of information in an environment of reduced group pressure to conform and remove the impact of the dominant individual (4:63).

For this study, a series of questions, in three rounds, was developed, via the DELPHI procedure to gather the entropy data. The first round responses formed the basis for each successive round by identifying features considered to be uncertain as to outcome. The specific set of questions is detailed in Appendix A together with specific response summaries. The questions were reviewed and approved by members of the Air Force Institute of Technology faculty for sufficiency with respect to expected results.

The aspects shown in Appendix A, Summary of Round I Responses (p. 103), represent all the uncertain areas of the F-5E program as identified by collective opinion of the group of experts participating under the DELPHI procedure. In Appendix A, Tables 6 and 7 (pp. 106-110), the number in each cell represents the arithmetic average of the responses for that particular probability in the cell. These data were used to compute the value of entropy outlined in a subsequent section of the chapter.

DATA ANALYSIS

Cost Prediction Data

The data collected for the measurement of entropy, via the DELPHI procedure, were reduced to two key variables: n, or the number of possible outcomes for the F-5E development program; and p_i, or the probability associated with the i^{th} outcome. Using the DELPHI procedure, there were 12 aspects identified as uncertain in outcome and three feature outcomes for each aspect. The probabilities associated with the outcome aspects are listed later in Table 7, Appendix A (pp. 109-110).

Since none of the participants responded to the feature outcome category labeled "Unacceptably Excellent," this category was removed from further consideration in determining possible program variances. Therefore, a program outcome was defined as a set of 12 aspects, each associated with one of the 2 possible feature outcomes in this particular research and shown in Table 8, Appendix A (p. 111). This definition produced a total 4,096 possible program outcomes. The probability of a program outcome was defined as the product of the probabilities of one feature outcome taken from each of the 12 aspects associated with the program outcome, assuming independence among the aspects (refer to Appendix B, p. 113, for detailed discussion on the derivation of these outcomes).

To compute the numerical value of entropy, a short FORTRAN IV computer program developed by Glover and Lenz, was used. The program is discussed and listed in Appendix B (pp. 115 and 116 respectively). The results of the calculation for the value of entropy are:

$$h = \frac{H_{max}}{H_{sum}} = .910$$

Martin Cost Model Prediction

To use the Martin Cost Model to predict final total cost of the F-5E development program, the formula is:

$$C_E = \frac{C_I}{1 - h} \quad (23:126)$$

A cost forecast was made at T_O using information developed during the analysis. C_I is the initial contract target price taken from the development contract. Relative entropy, h, is calculated with information derived from the DELPHI procedure concerning expected outcomes at T_n, projected from T_O. The calculation of C_E is as follows:

$$C_E = \frac{C_I}{1 - h} = \frac{83.635}{1 - .91} = \frac{83.635}{.09}$$

where 1 - h = IE.

$$C_E = \$929.278 \text{ million.}$$

Thus, the estimated total program cost is $929.278 million as compared to an actual program development cost of $89.322 million. This estimated total program development cost, C_E, represents a figure 10.4 times greater than the actual total program development cost.

It is evident from a comparison of the actual to estimated total program development cost, a great difference, that the Martin Cost Model did not work as designed. With a decrease in informational efficacy, program costs increace. Based on the outcome of the DELPHI procedure and the probabilities assigned by the participants, a relative entropy of .91 was calculated in the F-5E study.

Since relative entropy, h, is a measure of the degree of uncertainty in a situation, this outcome indicates that an extremely high degree of uncertainty does exist.

DATA SUMMARY

This chapter presented the methodology and specific results associated with data collection and test performed with respect to the research hypothesis. Actual cost data from the F-5E, TIGER II, development program was compared to the cost prediction generated by the Martin Cost Model. Based on the compared data, the Martin Cost Model does not even approach the figure for actual program development cost but exceeds it by over 900%. A further explanation of these results will be discussed in Chapter IV. From the results obtained thus far, the research hypothesis is not supported.

CHAPTER IV

ANALYSIS AND SUMMARY OF FINDINGS

Chapter III presented the procedures or methodology used for data collection, data analysis, and the test of the Martin Cost Model. The presentation also included, based upon that methodology, the calculation of the values required for testing and analyzing the ability of the model to accurately forecast or predict the final development cost for the F-5E, TIGER II, aircraft. In Chapter III, the findings were the opposite of what was expected, as reflected in the research hypothesis. Several areas were explored to explain the poor predictive power of the model.

As presented in Chapter III and Appendix C, the research hypothesis of the current study was not supported. The mathematical calculations of Appendix B along with the study comparisons of Appendix D reveal the Martin Cost Model does not hold under the current situation. Many factors contribute to the failure of the research hypothesis, but most significant was the difference of opinion and resultant assignment of probabilities to the alternatives summarized in DELPHI Round I. The results of this probability assignment produced a high entropy calculation yielding a low informational efficacy. Appendix E provides a comparison of participant answers and an analysis of the resultant dispersion. A discussion of other types of cost adjustment, the need for a prior facility with probability, and the DELPHI procedure itself is contained in this chapter.

APPLICATION OF COST ADJUSTMENTS

Within the Glover-Lenz study, consideration was given to possible adjustments to the actual final cost of the development program prior to applying the least-squares method of fitting a straight line through the cost observation data, c_I (16:64). Such adjustments would have been based upon changes in the actual costs which were attributable to ". . . causes external to the program . . . [16:64]," as in the case of abnormal cost escalations or externally directed changes to the weapon system's capability (16:64). Glover and Lenz concluded, however, that since the points in time at which such externally caused changes in cost should be removed could not be determined and since such adjustments would have had ". . . relatively small influence . . . [16:64]," the unadjusted final cost figure was retained.

While the same conclusion was assumed to be applicable within the current study, that conclusion was of minor importance. Though there are methods available to take cost adjustments into consideration, they were not utilized. Instead, adjustments to the final cost of the development program were not considered appropriate in the present study due to the large difference between the estimated final development cost and the actual final development cost, a difference of over 900%.

BACKGROUND EXPERIENCE OF EXPERTS

In the weapon system acquisition process, the opinion of experts, based on their personal experience, is critical to the measurement of risk and uncertainty. These factors of risk and uncertainty, as measured by expert experience, contribute to the subjective probability that an event will occur. Expert opinion is based on experience, information, and intuition. This information, along with the manipulation of the information process yielding the calculation of entropy are two key concepts of the Martin Cost Model.

In the manipulation of the Martin Cost Model, a certain knowledge of and facility with probability and the potential impact of risk and uncertainty on the final development program cost are necessary for accurate predictions. This basic background is required to give the participants an understanding of the technique attempted.

The participants must "feel involved" in the study in order to provide complete cooperation on a voluntary basis.

CURRENT DELPHI PROCEDURE STATUS

The DELPHI procedure requires that participating panelists be experts in the subject area and that a consensus be obtained through reliable and valid procedures (24:4). However, Henry M. Parsons, in a 1972 study, concluded that the reliance of system designers or the opinions and preferences of ". . . experts" is "foolhardy." Such experts ". . . may provide suggestive leads, but are not reliable guides as demonstrated by repeated disagreement with objective data . . . [24:17]."

Another feature that must be considered is whether the group responses can be aggregated meaningfully. If there is no way to meaningfully aggregate group response, then the DELPHI procedure would probably have questionable results. External pressures to conform to "popular" or top level management decisions or a desire to avoid "rocking-the-boat" may seriously affect the DELPHI procedure (4).

Part of the basic foundation of the DELPHI is the guarantee of anonymity of participants involved. This facet serves the purpose of attracting expert panelists by guaranteeing protection against individual accountability and an invitation to "permissive brainstorming where anything goes." Lacking accountability, a participant can blame nameless others for any findings he does not like (24:62).

Inherent in the DELPHI are both independence and dependence between experts which is at the heart of the DELPHI iteration "with feedback." The first round of questions is designed to secure independent expert judgment. Successive rounds provide correlated or biased judgments (24:18). Rationalizations concerning reconsiderations, incorporation of new information, and convergence toward consensus cannot hide the fact that independent judgment is destroyed once the participants know how others responded (24:18). The DELPHI deliberately manipulates responses towards minimum dispersion of opinion in the name of consensus (24:47). By the time a third or fourth round occurs, the holdout individualist sees the possibility of another round of questioning and yields to save another round (24:49).

Complex future events do not lend themselves to clear and unambiguous descriptions typical of the one-sentence DELPHI questionnaire format. Vague, generalized descriptions of future events permit respondents to project any one of a large number of possible scenarios as his interpretation of the event. Verbal responses, when they occur, are vague with sweeping descriptions, slogans, or simplistic statements. The structure and dynamics of the DELPHI response contribute to compounding ambiguity (24:49).

DELPHI items are typically broad, amorphous classes of events not precisely defined. DELPHI forecasts are opinions about these broad classes of events, not systematic predictions. Opinions are typically snap judgments based on free-association stereotypes. Opinion consensus tends to be manipulated to minimize opinion dispersion. The DELPHI procedure produces transient attitudes about the future, which is quite different from systematic predictions of the future. The DELPHI questionnaire format does not lend itself to scientifically objective and externally verifiable statements of future events (24:61).

> Accuracy can not be measured for most DELPHI items, because changing attitudes and opinions on amorphous issues are not true or false and do not have specific dates at which they occur [24:61].

There is nothing basically wrong with studying and learning more about opinions concerning the future. We should not confuse such opinions, however, with seriously considered, qualified and documented predictions of well-defined future developments. Attitudes and opinions change; fresh sampling in real time is needed to track these changes. Sampling must be explicit in terms of subject populations if any systematic inferences are to be made (24:61).

The originators of the DELPHI procedure had the right idea in answer to a pressing need to enlist the aid of geographically separated experts to work together on unknown and complex problems. One of the most significant aspects of their work was the accumulation of knowledge through a series of interactions and feedback. This concept answered the social need, but implementation has been counterproductive. Instead of testing numerous alternatives, the method zeroed in on iterative group response (24:72).

SUMMARY

As applied to the current study, the DELPHI procedure did not provide evidence to substantiate the ability of the Martin Cost Model to predict final program development costs. In actuality, the opposite effect of what had been the research hypothesis occurred and the research hypothesis was not supported.

In analyzing the data obtained from the F-5E participants, a significant difference of opinion and probability assignment to cited areas of uncertainty were noted. This may have resulted for numerous reasons ranging from a lack of facility for probability assignment through a failure to believe anonymity would be maintained coupled with a "do not rock-the-boat" attitude. Based on these aspects and others previously mentioned in Chapter IV, the DELPHI procedure leaves much to be desired. It appears to be a poor tool to obtain data for use with the Martin Cost Model. Some other technique or combination of techniques should be investigated to determine if one exists which is capable of providing accurate and readily useable information for use with the Martin Cost Model.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Within this chapter, the final conclusions for the current study will be presented. Following the conclusions will be the recommendations for future research into the area of testing the validity of the Martin Cost Model as a predictor of final development cost and as a tool with which to predict and control cost growth.

CONCLUSIONS

In fulfilling the national policies and objectives of the United States, the DoD must insure that military weapon system sophistication is maintained and increased as technology advances throughout the world. The resources of society, however, are limited. Competition for the resources that are available have increased between the various sectors of society. The DoD is in competition with the growing public demands for non-military related governmental programs and services. Granted, total federal expenditures have increased. However, in terms of available dollars, the proportion that has been allotted to the DoD for military purposes has continued to shrink while the costs of maintaining and upgrading weapon system sophistication has grown at a disproportionate rate. To continue to fulfill national defense policies and objectives, ways must be found to judiciously manage those limited resources that are allocated to the DoD. One avenue available to manage allotted resources is to develop a method to curtail cost growth in military weapon system acquisition programs.

The subject of the current study, the Martin Cost Model, is a recent attempt to formulate a technique to deal with potential and existing cost growth. The Martin Cost Model is a mathematical model into which such concepts as entropy, informational efficacy, cost, and time have been integrated for the purpose of providing a predictive managerial tool for weapon system development cost. The application of the model to a development program rests upon certain assumptions referent to cost growth and weapon system development program management. These assumptions are listed here in summary form:

1. The cost growth definition assumes no change in quantity produced.

2. The program manager, contractor, and associated information form an information system.

3. A condition of total information in a system equates to unity.

4. The program manager is experienced.

5. The Martin Theory is descriptive, not normative.

6. The effective program cost may be represented by a ratio of target price to informational efficacy of the data in a closed decision system.

costs of maintaining and upgrading weapon system sophistication has grown at a disproportionate rate. To continue to fulfill national defense policies and objectives, ways must be found to judiciously manage those limited resources that are allocated to the DoD. One avenue available to manage allotted resources is to develop a method to curtail cost growth in military weapon system acquisition programs.

The subject of the current study, the Martin Cost Model, is a recent attempt to formulate a technique to deal with potential and existing cost growth. The Martin Cost Model is a mathematical model into which such concepts as entropy, informational efficacy, cost, and time have been integrated for the purpose of providing a predictive managerial tool for weapon system development cost. The application of the model to a development program rests upon certain assumptions referent to cost growth and weapon system development program management. These assumptions are listed here in summary form:

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2. The program manager, contractor, and associated information form an information system.

3. A condition of total information in a system equates to unity.

4. The program manager is experienced.

5. The Martin Theory is descriptive, not normative.

6. The effective program cost may be represented by a ratio of target price to informational efficacy of the data in a closed decision system.

7. Entropy is a measure of disorder in an information system.

8. The economic environment of a weapon system acquisition program may reflect perfect economic competition but it is deemed highly improbable.

9. The information subsystem, characterized by a closed loop system, assumes:

a. Uncertainty can be equated to risk and measured by the amount of entropy in the information subsystem.

b. Negentropy can be measured as the remainder when the value of relative entropy is subtracted from unity.

10. Informational efficacy varies inversely with information in the information subsystem.

11. All terms reflecting cost or price in the model refer to economic cost consisting of the contractor's costs and profits.

12. There are no limitations imposed directly on the Martin Cost Model.

If these assumptions are correct, then the basis for prediction and managerial control rests in the measure of entropy. This implies the ability of the program manager's information system to identify all possible alternative program outcomes and accurately assess the alternatives in probabilistic terms does exist. To the extent that such abilities are inadequate, the usefulness of the model as a tool rapidly declines.

The question as to whether the Martin Cost Model is a viable technique for predicting and managing final weapon system development cost or not still remains unanswered. On the surface, the results of the present study indicate that this model has failed to predict and manage cost. The model predicted a final development cost for the F-5E, TIGER II, aircraft which was 10.4 times greater that the actual final cost. The initial contract price for development was within 6.37% of the final cost. The conclusions of this study are the exact opposite of that reached in the Glover-Lenz study even after the discrepancies in data presentation and inappropriateness of the statistical test employed are considered as shown in Appendix C and D.

In the Glover-Lenz study, the Martin Cost Model was found to be a viable technique. The model predicted a final development cost for the SRAM which was only 3.9% greater than the actual final cost. Aside from the conclusions drawn from the two studies, the only major difference is one of situation. While both studies used the same basic data collection technique centered around the DELPHI procedure, the data base for one study rested upon the development phase of the SRAM missile while the other study rested upon the F-5E, TIGER II, aircraft. The answer to the model viability question appears to reside in determining the utility of the concept of entropy upon which the cost prediction of the model rests. The utility can be determined only through further research into discovering and applying a means of measuring, with accuracy, the entropy of the model in a given development program. The disparity between the results of the two studies lead to the conclusion that the DELPHI procedure is not universally applicable to all situations.

RECOMMENDATIONS

On a conceptual level, the Martin Cost Model appears to be a potentially viable technique for predicting and controlling weapon system development costs. The difficulty, however, comes in attempting to apply the model. As indicated previously, the difficulty centers upon determining the utility of the concept of entropy as a basis for predicting cost and measuring, with accuracy, the entropy involved in a development situation. If specific means for making such a measurement had been available, the results of the current study might have been different. As a comparison of the results of the two studies has shown, the model can yield dramatically different results. This does not mean that the Martin Cost Model should be ignored but, rather suggests further study is appropriate with emphasis on the following areas:

1. Expand the research effort to define and develop some way other than the DELPHI procedure to measure outcome probability.

2. Based on the results of the above research, a decision should be made as to the feasibility of applying the model in a real world context. If the model is to be applied and the results analyzed, a historical frame of reference undoubtedly will be used since application of the model to an on-going development program would take years to complete. In using actual historical data, however, greater efforts should be taken to obtain information about the detailed circumstances surrounding the actual development program. With such information, it would be possible to perform a more valid test of the predictive accuracy of the model.

3. In studying and applying the model, further research should be devoted to developing statistical procedures for testing the model.

SUMMARY

The present study has cast doubt on the usefulness of the Martin Cost Model as a predictive and managerial tool with which to address cost associated with the development stage of a weapon system. The final determination as to the usefulness of the model rests in further analysis of the utility of the concept of entropy or uncertainty as it relates to decision making and the occurrence of cost plus the development of a means to accurately measure entropy. Regardless of the ultimate disposition of the Martin Cost Model, it should be recognized that the model has already been of some value. It has reemphasized that the determination and management of development program costs are functions of the quality or adequacy of the information system upon which the program manager bases his decisions.

APPENDIXES

APPENDIX A

COLLECTION OF DATA FOR MEASURING ENTROPY

This appendix presents the questions and responses of the DELPHI procedure explained in Chapter III. The DELPHI procedure would normally involve four rounds of interrogation (6:6) but, due to responses received in Round III, Round IV was not considered necessary. The following sections present the questions and responses for each individual round.

ROUND I

In Round I, the scenario was established which was used for the remaining rounds of interrogation.

Round I Questions

The following questions were used in Round I:

Question 1. List those aspects - technical characteristics, performance parameters, physical characteristics - for the F-5E development phase, about which you felt the outcome could have been something other than acceptable (not including cost).

Question 2. In answer to the above question, when, in relation to the contract award date, were the aspect(s) evident?

Question 3. How does the F-5E, TIGER II, differ from other F-5 series aircraft?

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Question 4. What system(s)/component(s) contributed to the greatest delays?

Question 5. What information/data was available/ usable from previous F-5 series aircraft?

Question 6. Was this information/data used?

Question 7. How was this data used?

Responses to Round I Questions

The answers of each respondent are listed below by individual interrogated.

Participant 1. Participant number 1 answered the questions as follows:

1. Question 1. The following aspects were identified:

a. Aircraft Engines. The requirement for this fighter aircraft was to utilize the same size and weight engine as the earlier model F-5, but increase the thrust produced by the engines. It was a high technical risk area using new metals.

b. Fire Control Radar. Previous models did not have a radar set group. The development of a new, miniaturized set to fit in the structural dimensions of the F-5E nose section was undertaken.

c. Lead Computing Gun Sight. This was a new system added onto the F-5 series aircraft. There was some difficulty integrating the systems and obtaining an operationally acceptable product. Previous models used an optical sight.

2. Question 2. These aspects became evident about 6 months to a year after the contract award date.

3. Question 3. Engines were changed; Radar and Lead Computing Gun Sight were added.

4. Question 4. Engines and Fire Control Radar.

5. Question 5. All previous T-38 and F-5 test data available were used to hasten the F-5E development.

6. Question 6. Yes.

7. Question 7. Predetermine areas which might cause delays.

Participant 2. Participant number 2 answered the questions as follows:

1. Question 1. The following aspects were identified:

a. Aircraft Engines. The aircraft design called for new, more powerful engines in, basically, the same dimensional area as the previous model.

b. Lead Computing Sight. (Same as Lead Computing Gun Sight) New addition to the F-5 series aircraft.

c. Radar. (Same as Fire Control Radar) New addition to the F-5 series aircraft.

2. Question 2. Problems were encountered with the Radar and Lead Computing Gun Sight about nine to twelve months into the Research and Development (R&D) Program. Engine problems were encountered approximately one and one-half years into the R&D program.

3. Question 3. The F-5E differs from other F-5 series aircraft because it has: two position nose gear; J85GE-21 engines in lieu of -13 engines; Search and Range Radar with a Lead Computing Gun Sight; maneuvering flaps and a tail hook.

4. Question 4. The system contributing to the greatest delay was the J85GE-21 engines.

5. Question 5. All data generated by the earlier F-5 model aircraft was available for use and comparison.

6. Question 6. Yes.

7. Question 7. The data was used by the Source Selection Control Panel for comparative purposes.

<u>Participant 3</u>. Participant number 3 answered the questions as follows:

1. <u>Question 1</u>. The following aspects were identified:

a. <u>Boattail Design</u>. The design was acceptable but there was a fabrication problem, using titanium, which required more hours than originally anticipated.

b. <u>Environmental Control System</u>. The original system experienced bearing failure and did not keep the pilot cool enough.

c. <u>Fire Control Radar</u>. Several problems became evident when the radar set was built: it could not be used at night or in bad weather; the image was "washed out" in the sun; poor Mean Time Between Failures (MTBF).

d. <u>Inadequate Tooling</u>. Tooling and set-up were inadequate to meet the originally specified production rate. The problem was solved by dropping the rate to a maximum of 18 per month.

e. <u>Pass Fatigue Test Within Time Schedule</u>. Some structural fatigue was experienced during testing requiring modification.

2. <u>Question 2</u>. Problems were encountered with the Fire Control Radar and Environmental Control System some time after the start of the test program in 1973. Fatigue testing problems were encountered about three to four years after the contract award date (1973-1974) when testing got to 8000 aircraft hours. Boattail design problems were evident in the first year to eighteen months; inadequate tooling was evident in the first year.

3. <u>Question 3</u>. The F-5E is dimensionally larger with more powerful J85GE-21 engines. It has a titanium boattail, maneuvering flaps, and a Fire Control Radar/ Lead Computing Optical Sight System (FCR/LCOSS).

4. <u>Question 4</u>. The -21 engines were the greatest single problem; they had not been previously foreseen as a problem area. Problems encountered were:

a. Fifth and sixth stage compressor problems.

b. Flameouts in certain portions of the envelope.

c. Variable Exhaust Nozzle problems.

5. Question 5. Technical data was available because of the assumed similarity between A/B and E models. Only limited pricing data was used because prior aircraft were on a firm fixed price basis and the F-5E is on an incentive contract.

6. Question 6. A great deal of the technical data was used initially. Pricing data was not used extensively because commonality did not appear high and data had not been collected in a consistent manner.

7 Question 7. The available historical data was used to compare learning curves for pricing and estimating purposes. It was also used to qualify or approve a design because it was common to the F-5A/B. This belief in commonality caused some problems since commonality did not appear to be as high as originally expected.

Participant 4. Participant number 4 answered the questions as follows:

1. Question 1. The following aspects were identified:

a. AGE Problems. Aerospace Ground Equipment (AGE) design followed hardware design thereby lessening lead time to production.

b. GFAE Problems. Government Furnished Aerospace Ground Equipment (GFAE) required long lead time versus delivery; the rejection rate was also high.

c. Logistic Problem. There was some difficulty with late spare equipment and unserviceable common AGE.

d. Manufacturing Problem. There was a high learning curve with the F-5E.

e. Pass Fatigue Test Within Time Schedule. There was some uncertainty that the F-5E would pass the fatigue program on time. Retrofitting was necessary to extend service life to 4000 hours.

f. Pass Flight Test Within Time Schedule. New development projects added to the F-5E caused slippage.

2. Question 2. In relation to the contract award date, these aspects became evident at varied times throughout the program.

3. Question 3. The F-5E has improved performance and heavier weight.

4. Question 4. The boattail in the aft fuselage section and the Radar set caused the greatest delays.

5. Question 5. All F-5A/B and T-38 specifications were available for use.

6. Question 6. Yes.

7. Question 7. The information was used to assure off-the-shelf design standardization.

Summary of Round I Responses

The following is a summary of uncertain aspects of the F-5E, TIGER II, Development Program.

1. AGE Problem. AGE design followed hardware design therefore lessening lead time to produce.

2. Boattail Design. Fabrication using titanium metal required more hours than originally anticipated.

3. Environmental Control System. Bearing failure and insufficient cooling were weak areas.

4. Engines. Redesign was necessary to produce more thrust with equal or less overall engine weight.

5. Fire Control Radar. Miniaturization and operational interfacing problems caused delays.

6. GFAE Problem. Lead time versus delivery time led to difficulties; rejection rate was high.

7. Inadequate Tooling. Tooling and set-up were inadequate to meet the originally specified production rate; design problems complicated matters.

8. Lead Computing Gun Sight. Development and integration of new system caused some difficulty.

9. Logistic Problem. Late spares plus unserviceable common AGE increased delays.

10. Manufacturing Problems. There was a high learning curve involved in this production.

11. Pass Fatigue Test Within Time Schedule. Discovery of fatigue areas required retrofiting to attain 4000 hour service life.

12. Pass Flight Test Within Time Schedule. New development projects caused slippage.

ROUND II

Round II of the DELPHI procedure elicited probability distributions for the aspects identified by the participants in Round I. The question used in this round included a summary of the responses to Round I.

Round II Question

The following is a summary of uncertain aspects of the F-5E, TIGER II, Development Program. We now ask you to assess the probability of the outcome of an aspect being in one of the given zones. The sum of the three probabilities for each aspect must be 1.0. A brief statement of your reasons is also necessary. Consider each aspect individually.

Aspect	Unacceptably Poor (Unsatisfactory)	Acceptable (O.K.)	Unacceptably Excellent (Too Good)
AGE Problem	p=	p=	p=
Boattail Design	p=	p=	p=
Environmental Control Sys	p=	p=	p=
Engines	p=	p=	p=
Fire Control Radar	p=	p=	p=
GFAE Problem	p=	p=	p=
Inadequate Tooling	p=	p=	p=

Aspect	Unacceptably Poor (Unsatisfactory)	Acceptable (O.K.)	Unacceptably Excellent (Too Good)
Lead Computing Gun Sight	p=	p=	p=
Logistic Problem	p=	p=	p=
Manufacturing Problem	p=	p=	p=
Pass Fatigue Test w/i Time Schedule	p=	p=	p=
Pass Flight Test w/i Time Schedule	p=	p=	p=

NOTE: For the purpose of this and subsequent questions, the term acceptability is defined as the contract specification at development award time plus or minus an amount that would have defined acceptability for you. Do not attempt to quantify the range. Simply conceive of acceptable outcomes as a range of values. Precise measurement of parameters is not the objective of this experiment.

Responses to Round II Question

Table 6 contains the response of continuing participants to the Round II question. It should be noted at this point that only the responses from 3 participants are listed in the Round II question table.

To maintain a semblance of continuity of information and train of thought, data collection was designed to cover a 10 working day period from start to finish. Long periods of time delay between sessions could possibly be detrimental to the study in that participants may not be able to reproduce their rationale (4:62). Due to an unexpected temporary duty (TDY) commitment across country

Table 6

Summary of Round II Responses to DELPHI Interrogation

Aspect Number	Participant Number	Unacceptably Poor	Acceptable	Unacceptably Excellent
1	1	0.05	0.95	0.00
	2	0.20	0.80	0.00
	3	0.80	0.20	0.00
2	1	0.05	0.95	0.00
	2	0.80	0.20	0.00
	3	0.20	0.80	0.00
3	1	0.10	0.90	0.00
	2	0.50	0.50	0.00
	3	0.60	0.40	0.00
4	1	0.25	0.75	0.00
	2	0.30	0.70	0.00
	3	0.20	0.80	0.00
5	1	0.30	0.70	0.00
	2	0.70	0.30	0.00
	3	0.80	0.20	0.00
6	1	0.15	0.85	0.00
	2	0.20	0.80	0.00
	3	0.40	0.60	0.00
7	1	0.15	0.85	0.00
	2	0.70	0.30	0.00
	3	0.00	1.00	0.00
8	1	0.25	0.75	0.00
	2	0.80	0.20	0.00
	3	0.20	0.80	0.00
9	1	0.20	0.80	0.00
	2	0.70	0.30	0.00
	3	0.80	0.20	0.00
10	1	0.15	0.85	0.00
	2	0.80	0.20	0.00
	3	0.50	0.50	0.00

Table 6 (continued)

Aspect Number	Participant Number	Unacceptably Poor	Acceptable	Unacceptably Excellent
11	1	0.10	0.90	0.00
	2	0.60	0.40	0.00
	3	0.00	1.00	0.00
12	1	0.10	0.90	0.00
	2	0.80	0.20	0.00
	3	0.00	1.00	0.00

during the data gathering period, further participation by participant number 4 was discontinued in Rounds II and III. All the data accumulated from the four participants in Round I were utilized in Rounds II and III under the assumption that they would not bias the study. Since the DELPHI procedure utilizes anonymity of source information, iterative controlled feedback, and statistical group response (4:45), no adverse affect was anticipated.

ROUND III

Round III Question

The following question was used in Round III:

> Below are listed the responses for each aspect of Round II. If you wish to change any of the responses in light of the summarized information, please do so by striking out the number shown and enter another number. Please state your reasons for any change you might make.

Responses to Round III Question

The responses to the above question are presented in summary form in Table 7.

Changes

There were no changes in Round III using the data from Round II. The probabilities that were obtained from Round III were used to measure the entropy required for using the Martin Cost Model to predict total program cost for the F-5E development program (see Appendix B and Chapter III). Table 8 contains the probabilities from the entropy data collection.

Table 7

Summary of Round III Responses to the DELPHI Interrogation

Aspect Number	Participant Number	Probability of Unacceptably Poor	Probability of Acceptability	Probability of Unacceptably Excellent
1	1	0.05	0.95	0.00
	2	0.20	0.80	0.00
	3	0.80	0.20	0.00
2	1	0.05	0.95	0.00
	2	0.80	0.20	0.00
	3	0.20	0.80	0.00
3	1	0.10	0.90	0.00
	2	0.50	0.50	0.00
	3	0.60	0.40	0.00
4	1	0.25	0.75	0.00
	2	0.30	0.70	0.00
	3	0.20	0.80	0.00
5	1	0.30	0.70	0.00
	2	0.70	0.30	0.00
	3	0.80	0.20	0.00
6	1	0.15	0.85	0.00
	2	0.20	0.80	0.00
	3	0.40	0.60	0.00
7	1	0.15	0.85	0.00
	2	0.70	0.30	0.00
	3	0.00	1.00	0.00
8	1	0.25	0.75	0.00
	2	0.80	0.20	0.00
	3	0.20	0.80	0.00
9	1	0.20	0.80	0.00
	2	0.70	0.30	0.00
	3	0.80	0.20	0.00
10	1	0.15	0.85	0.00
	2	0.80	0.20	0.00
	3	0.50	0.50	0.00

Table 7 (continued)

Aspect Number	Participant Number	Probability of Unacceptably Poor	Probability of Acceptability	Probability of Unacceptably Excellent
11	1	0.10	0.90	0.00
	2	0.60	0.40	0.00
	3	0.00	1.00	0.00
12	1	0.10	0.90	0.00
	2	0.80	0.20	0.00
	3	0.00	1.00	0.00

Table 8

Entropy Data Collection Results

Aspect	Outcome Probabilities: Unacceptably Poor	Acceptable	Unacceptably Excellent
AGE Problem	.350	.650	0.00
Boattail Design	.350	.650	0.00
Environmental Control Sys	.400	.600	0.00
Engines	.250	.750	0.00
Fire Control Radar	.600	.400	0.00
GFAE Problem	.250	.750	0.00
Inadequate Tooling	.280	.720	0.00
Lead Computing Gun Sight	.417	.583	0.00
Logistic Problem	.560	.440	0.00
Manufacturing Problem	.483	.517	0.00
Pass Fatigue Test w/i Time Schedule	.233	.767	0.00
Pass Flight Test w/i Time Schedule	.300	.700	0.00

APPENDIX B

COMPUTATION OF F-5E PROGRAM ENTROPY

The results of the DELPHI data collection with respect to the F-5E, TIGER II, development program, are summarized in Chapter III (p. 81) and shown in Appendix A. Appendix B will explain the details of computing entropy given the conditions specified by the DELPHI results.

ENTROPY CALCULATION FORMULA

The formula for determining entropy is:

$$h = \frac{H}{H_{max}} = \frac{-\sum_{i=1}^{m} p_i \log p_i}{\log m}$$

where: m = number of possible outcomes

p_i = probability of i^{th} outcome

H = unadjusted entropy value

H_{max} = maximum entropy

h = expression of relative disorder or entropy

In the case of the F-5E DELPHI results, a total of 12 program aspects, each with three possible outcomes, were identified. The specific outcome of each of the 12

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aspects described a program outcome. Assuming independence among aspects, the probability of a program outcome is evaluated as the product of each of the 12 specific outcome probabilities (16:100).

The number of possible outcomes is derived from each program as the number of possible combinations of two things (aspect outcomes) taken one at a time (specific aspect outcome) (16:101). A program outcome is a sequence of twelve aspect outcomes, and may be evaluated as follows:

Number of aspect outcomes = $\binom{3}{1}$ (16:101)

Sequence of twelve aspects =

$$\binom{2}{1}^{12} = \left(\frac{2!}{1!1!}\right)^{12} = 2^{12} = 4096 \text{ program outcomes.}$$

During the data gathering process, the participants expressed their probabilities as either Unacceptably Poor or Acceptable. The category labeled Unacceptably Excellent was eliminated by the participants as nonexistent and therefore was eliminated as a possible outcome for our computational formulation.

ENTROPY COMPUTER PROGRAM

A modified version of Glover-Lenz computer program in FORTRAN IV programming language was used on the Air Force Logistics Command CREATE computer system. The program listing is shown in Figure 11 with Variable Names and Definitions in Table 9.

```
Ø1Ø DIMENSION PMAT(12,2)
Ø15 DOUBLE PRECISION PEVENT,PSUM,PLOG,HSUM,HMAX,H,NE
Ø2Ø PRINT,"INPUT THE PROBABILITY MATRIX ROW-WISE."
Ø3Ø READ,((PMAT(I,J),J=1,2),I=1,12)
Ø35 NE = Ø
Ø4Ø EVNTNO=Ø
Ø5Ø PSUM=Ø
Ø6Ø HSUM=Ø
Ø7Ø DO 1Ø I1=1,2
Ø8Ø DO 1Ø I2=1,2
Ø9Ø DO 1Ø I3=1,2
1ØØ DO 1Ø I4=1,2
11Ø DO 1Ø I5=1,2
12Ø DO 1Ø I6=1,2
13Ø DO 1Ø I7=1,2
14Ø DO 1Ø I8=1,2
15Ø DO 1Ø I9=1,2
16Ø DO 1Ø I1Ø=1,2
17Ø DO 1Ø I11=1,2
18Ø DO 1Ø I12=1,2
19Ø PEVENT=PMAT(1,I1)*PMAT(2,I2)*PMAT(3,I3)*PMAT(4,I4)*PMAT(5,I5)*
2ØØ&PMAT(6,I6)*PMAT(7,I7)*PMAT(8,I8)*PMAT(9,I9)*PMAT(10,I1Ø)*
21Ø&PMAT(11,I11)*PMAT(12,I12)
22Ø PSUM=PSUM + PEVENT
23Ø PLOG=PEVENT*ALOG1Ø(PEVENT)
24Ø HSUM=HSUM + PLOG
25Ø EVNTNO=EVNTNO + 1.
26Ø 1Ø CONTINUE
27Ø HMAX=ALOG1Ø(EVNTNO)
28Ø HSUM=HSUM*(-1.Ø)
29Ø H=HSUM/HMAX
295 NE = 1-(H)
3ØØ PRINT,"H=                        ",H
3Ø5 PRINT,"NE=                       ",NE
31Ø PRINT,"HSUM=                     ",HSUM
32Ø PRINT,"HMAX=                     ",HMAX
33Ø PRINT,"EVNTNO=                   ",EVNTNO
34Ø PRINT,"PSUM=                     ",PSUM
35Ø STOP
36Ø END
```

Figure 11

Entropy Computation Program
Coding

Table 9

Variable Names and Meaning

Variable Name	Meaning
PMAT	A matrix of program feature outcome probabilities.
I,J	Indices for the PMAT matrix.
EVNTNO	Number of program outcomes.
PSUM	Sum of the program outcome probabilities.
HSUM	Sum of the products p_i log p_i.
PEVENT	Probability of a program outcome.
PLOG	Product of PEVENT and $\log_{10}$ PEVENT.
HMAX	The maximum entropy ($\log_{10}$ EVNTNO).
H	The expression of relative entropy.
NE	The degree of order in the system, 1 - relative entropy.
I1,...,I9	DO Loop counters.

To insure the reliability of the Glover-Lenz Entropy Computation Program, a small version, as test, was manually calculated. The data and results are in Table 10. The computer program for these calculations is listed in Figure 12 with results in Figure 13.

Table 10

Data and Results of 2 x 2 Manual Calculation

	Outcome	
Aspect	Poor	Acceptable
1	.5	.5
2	.3	.7

The total number of events possible are:

$$\binom{2}{1}^2 = \left(\frac{2!}{1!1!}\right)^2 = 4 = m \quad (33:121-123)$$

$$\begin{array}{lll} & p_i & \\ (.5)(.3) = .15 & & (.3)(.5) = .15 \\ (.5)(.7) = .35 & & (.7)(.5) = .35 \end{array}$$

$$H_{sum} = -\sum p_i \log p_i$$

$$= -(.15)(-.823909) = (.1235863)(2) = .2471726$$
$$= -(.35)(-.455932) = (.1595762)(2) = \underline{.3191524}$$

$$H_{sum} = .5663250$$

$$H_{max} = \log m = \log 4 = .60206$$

$$h = \frac{H_{sum}}{H_{max}} = \frac{.5663250}{.60206} = .9406454$$

```
Ø1Ø DIMENSION PMAT(2,2)
Ø2Ø PRINT,"INPUT NOW"
Ø3Ø READ,((PMAT(I,J),J=1,2),I=1,2)
Ø4Ø EVNTNO=Ø
Ø5Ø PSUM=Ø
Ø6Ø HSUM=Ø
Ø7Ø DO 1Ø I1=1,2
Ø8Ø DO 1Ø I2=1,2
Ø9Ø PEVENT=PMAT(1,I1)*PMAT(2,I2)
1ØØ PSUM=PSUM + PEVENT
11Ø PLOG=PEVENT*ALOG1Ø(PEVENT)
12Ø HSUM=HSUM+PLOG
13Ø EVNTNO=EVNTNO + 1
14Ø 1Ø CONTINUE
15Ø HMAX=ALOG1Ø(EVNTNO)
16Ø HSUM=HSUM*(-1.Ø)
17Ø H=HSUM/HMAX
18Ø PRINT,"H=              ",H
19Ø PRINT,"HMAX=           ",HMAX
2ØØ PRINT,"HSUM=           ",HSUM
21Ø PRINT,"EVNTNO=         ",EVNTNO
22Ø PRINT,"PSUM=           ",PSUM
23Ø STOP
24Ø END
```

Figure 12

Modified 2 x 2 Entropy
Computer Program

```
INPUT NOW
=.5,.5
=.3,.7
H=              Ø.94Ø64546E ØØ
HMAX=           Ø.6Ø2Ø5999E ØØ
HSUM=           Ø.56632499E ØØ
EVNTNO=         Ø.4ØØØØØØØE Ø1
PSUM=           Ø.1ØØØØØØØE Ø1
```

Figure 13

Data and Results of Modified 2 x 2
Entropy Computer Program

A second set of calculations, a little more complex than the first, were manually calculated with the data and results listed in Table 11. The results utilizing the computer program listed in Figure 14 are in Figure 15.

Table 11

Data and Results of 3 x 2
Manual Calculation

	Outcome	
Aspect	Poor	Acceptable
1	.5	.5
2	.3	.7
3	.2	.8

The total number of possible events are:

$$\binom{2}{1}^3 = \left(\frac{2!}{1!1!}\right)^3 = 2^3 = 8 = m \quad (33:121\text{-}123)$$

p_i	p_i
(.5)(.3)(.2) = .03	(.5)(.3)(.2) = .03
(.5)(.3)(.8) = .12	(.5)(.3)(.8) = .12
(.5)(.2)(.7) = .07	(.5)(.2)(.7) = .07
(.5)(.7)(.8) = .28	(.5)(.7)(.8) = .28

$$H_{sum} = -\sum p_i \log p_i$$

$$= -(.03)(-1.522878745) = (.0456863623)(2) = .0913727246$$
$$= -(.12)(-.920818754) = (.1104982505)(2) = .220996501$$
$$= -(.07)(-1.15490196) = (.0808431372)(2) = .1616862744$$
$$= -(.28)(-.5528419687) = (.1547957512)(2) = \underline{.3095915024}$$

$$H_{sum} = .7836470024$$

$$H_{max} = \log m = \log 8 = .903089987$$

$$h = H_{sum}/H_{max} = .7836470024/.903089987 = .8677396646$$

```
1Ø DIMENSION PMAT(3,2)
2Ø PRINT,"INPUT THE PROBABILITY MATRIX ROW-WISE."
3Ø READ,((PMAT(I,J),J=1,2),I=1,3)
4Ø EVNTNO=Ø
5Ø PSUM=Ø
6Ø HSUM=Ø
7Ø DO 1Ø I1=1,2
8Ø DO 1Ø I2=1,2
9Ø DO 1Ø I3=1,2
1ØØ PEVENT=PMAT(1,I1)*PMAT(2,I2)*PMAT(3,I3)
11Ø PSUM=PSUM+PEVENT
12Ø PLOG=PEVENT*ALOG1Ø(PEVENT)
13Ø HSUM=HSUM+PLOG
14Ø EVNTNO=EVNTNO+1
15Ø 1Ø CONTINUE
16Ø HMAX=ALOG1Ø(EVNTNO)
17Ø HSUM=HSUM*(-1.Ø)
18Ø H=HSUM/HMAX
19Ø PRINT,"H=    ",H,"    HSUM=    ",HSUM
2ØØ PRINT,"HMAX=    ",HMAX,"    EVNTNO=    ",EVNTNO
21Ø PRINT,"PSUM=    ",PSUM
22Ø STOP
23Ø END
```

Figure 14

Modified 3 x 2 Entropy
Computer Program

```
INPUT THE PROBABILITY MATRIX ROW-WISE.
=.5,.5,.3,.7,.2,.8
H=      Ø.86773967E ØØ    HSUM=     Ø.783647Ø1E ØØ
HMAX=      Ø.9Ø3Ø8999E ØØ    EVNTNO=     Ø.8ØØØØØØØE Ø1
PSUM=      Ø.1ØØØØØØØE Ø1
```

Figure 15

Data and Results of 3 x 2
Computer Calculation

```
1Ø DIMENSION PMAT(3,2)
2Ø PRINT,"INPUT THE PROBABILITY MATRIX ROW-WISE."
3Ø READ,((PMAT(I,J),J=1,2),I=1,3)
4Ø EVNTNO=Ø
5Ø PSUM=Ø
6Ø HSUM=Ø
7Ø DO 1Ø I1=1,2
8Ø DO 1Ø I2=1,2
9Ø DO 1Ø I3=1,2
1ØØ PEVENT=PMAT(1,I1)*PMAT(2,I2)*PMAT(3,I3)
11Ø PSUM=PSUM+PEVENT
12Ø PLOG=PEVENT*ALOG1Ø(PEVENT)
13Ø HSUM=HSUM+PLOG
14Ø EVNTNO=EVNTNO+1
15Ø 1Ø CONTINUE
16Ø HMAX=ALOG1Ø(EVNTNO)
17Ø HSUM=HSUM*(-1.Ø)
18Ø H=HSUM/HMAX
19Ø PRINT,"H=    ",H,"    HSUM=    ",HSUM
2ØØ PRINT,"HMAX=    ",HMAX,"    EVNTNO=    ",EVNTNO
21Ø PRINT,"PSUM=    ",PSUM
22Ø STOP
23Ø END
```

Figure 14

Modified 3 x 2 Entropy
Computer Program

```
INPUT THE PROBABILITY MATRIX ROW-WISE.
=.5,.5,.3,.7,.2,.8
H=      Ø.86773967E ØØ    HSUM=     Ø.7836470lE ØØ
HMAX=     Ø.9Ø3Ø8999E ØØ    EVNTNO=    Ø.8ØØØØØØØE Ø1
PSUM=     Ø.1ØØØØØØØE Ø1
```

Figure 15

Data and Results of 3 x 2
Computer Calculation

It is evident that the mathematical computations are compatible via manual and computer methods. The final results for the calculation of entropy are identical and the computer program is correct and functional.

The input data for the program is the series of 24 probability values from the DELPHI data collection, entered sequentially for each program feature. The program computes each F-5E program outcome probability, evaluates its logarithm to the base 10 and computes total entropy, maximum entropy, and relative entropy. The input and output for the computations in Chapter III are shown in Figure 16; the input values were taken from Table 8, Appendix A. These values represent an average value, by category, for each aspect.

```
INPUT THE PROBABILITY MATRIX ROW-WISE
=.35,.65
=.35,.65
=.4,.6
=.25,.75
=.6,.4
=.25,.75
=.28,.72
=.417,.583
=.56,.44
=.483,.517
=.233,.767
=.3,.7
H=                             Ø.91Ø11Ø2818746972 3ØD ØØ
NE=                            Ø.8988971812530277Ø7D-Ø1
HSUM=                          Ø.328764593543351697D Ø1
HMAX=                          Ø.36123599534129378ØD Ø1
EVNTNO=                        Ø.4Ø96ØØØØE Ø4
PSUM=                          Ø.999999998685666397D ØØ
```

Figure 16

F-5E Entropy Computation
Input and Output

APPENDIX C

STATISTICAL TEST OF THE MODEL

This appendix presents the calculations used to support the test of the Martin Cost Model as a predictor of program development cost. The F-test for homogeneity of variances was used to compare the following variances:

> Variance of Errors--Variance of errors measured from the observed quarterly cumulative costs to a least-squares line fitted to the actual cost observations.
>
> Variance of Deviations--Variance of the deviations measured from the observed quarterly cumulative costs to a predicted cost line based on the Martin Cost Model prediction for total program cost.

After the variances were calculated, they were compared to determine if they were from the same population variance. The F-test was used for this comparison.

CALCULATION OF VARIANCES

Least-Squares Line of Best Fit

Before the variance of the errors could be calculated, a least-squares line had to be fitted through the observed cost data and the errors of the cost points measured from the line. Using the assumption of linear cost and applying the method of least-squares to the observed cost data listed in Table 12, a least-squares line of best fit was computed. These cumulative cost figures for each quarterly time period were obtained through the F-5 International Fighter SPO's Financial Management Section and were based upon the Contract Funds Status Report (CFSR) for the F-5E. The CFSR is a report, published quarterly by the contractor, reflecting cumulative actual cost as of the calendar quarter.

The following steps were used to construct the equation for the least-squares line.

<u>Slope Computation</u>. The first step of the process was to calculate the slope of the line as follows (27:368-370):

$$m = \frac{14 \sum_{i=1}^{14} t_i c_i - \sum_{i=1}^{14} t_i \sum_{i=1}^{14} c_i}{14 \sum_{i=1}^{14} t_i^2 - \left(\sum_{i=1}^{14} t_i \right)^2}$$

Thus, $m = 6.8475$.

<u>Intercept Computation</u>. The next step was to calculate the vertical intercept (y) for the line (27:576).

$$y = \bar{c} - m\bar{t}$$

where: $\bar{t}$ = the mean number of quarters

m = slope of the line

Table 12

Quarterly F-5E Cumulative Cost Data

End Month	Year	Quarter (t_i)	Cumulative Cost (c_i) (in millions)
Mar	1971	1	4.510
Jun		2	10.573
Sep		3	20.833
Dec		4	38.299
Mar	1972	5	48.554
Jun		6	59.140
Sep		7	69.733
Dec		8	77.609
Mar	1973	9	81.081
Jun		10	83.224
Sep		11	84.399
Dec		12	86.253
Mar	1974	13	88.256
Jun		14	89.322

$\bar{c}$ = the mean of the observed costs

y = the vertical intercept of the line

Thus, y = 8.7713.

Therefore, the least-squares line representing the quarterly cumulative cost data is:

$$C_i = 8.7713 + 6.8475t_i$$

where: t_i = the i^{th} quarter during the development program, and

C_i = cumulative cost estimated at the end of the i^{th} quarter.

This equation was used to measure errors of the observed cost points from the least-squares line.

Variance of the Errors. The errors of the observed cost data from the least-squares line were calculated using the following equation:

$$e_i = c_i - C_i$$

where: c_i = observed cost for the i^{th} quarter

C_i = cost calculated for the i^{th} quarter using the least-squares equation

e_i = error for the i^{th} cost point measured from the least-squares line

The results of these calculations are presented in Table 13.

Calculation of the Variance. Following the measurement of the errors of the observed cost points from the least-squares line, the variance of errors was calculated. The

Table 13

Errors About Least-Squares Line

i	c_i	C_i	e_i
1	4.510	15.6188	-11.1088
2	10.573	22.4663	-11.8933
3	20.833	29.3138	-8.4808
4	38.299	36.1613	+2.1377
5	48.554	43.0088	+5.5452
6	59.140	49.8563	+9.2837
7	69.733	56.7038	+13.0292
8	77.609	63.5513	+14.0577
9	81.081	70.3988	+12.8252
10	83.224	77.2463	+5.9777
11	84.399	84.0938	+0.3052
12	86.253	90.9413	-4.6883
13	88.256	97.7888	-9.5328
14	89.322	104.6363	-15.3143

variance was calculated using the following equation (27:573):

$$S_e^2 = \frac{\sum_{i=1}^{n} e_i^2 - n\bar{e}^2}{n - 1}$$

where: n = number of quarters

e_i = error of the i^{th} cost point measured from the least-squares line

$\bar{e}$ = mean of the errors

S_e^2 = sample variance of the errors

The result of this calculation was $S_e^2 = 105.6178$. This variance was later compared with the variance of deviations in the F-test.

Variance of the Deviations

Before determination of the variance of the deviations, a cost prediction line using the Martin Cost Model prediction and the deviations of observed cost data points measured from this line was determined.

Predicted Cost Line. The calculations for measuring entropy for use in predicting the total program cost with the Martin Cost Model are found in Appendices A and B. The calculated total program cost was:

$$C_E = \frac{C_I}{1 - h} = \frac{83.635}{1 - .91} = \frac{83.635}{.09}$$

Therefore, the total program cost predicted by the model was \$929.278 million.

Using an assumption of linear cost, a line was drawn from the origin of the time-cost plane to the predicted cost point, $C_E = 929.278$ plotted at T_{14}. The point-slope method was used to determine the equation for this line as follows (16:111):

$$m = \frac{C_E - 0}{T_{14} - 0} = \frac{929.278}{14}$$

where: m = slope of the line

Therefore, the equation for the predicted cost line is:

$$C_{E_i} = 66.377T_i$$

where: T_i = i^{th} quarter

C_{E_i} = Martin Cost Model cost forecast at quarter T_i

Calculation of the Deviations. The following equation was used to calculate the deviations of observed cost data from the predicted cost line:

$$d_i = c_i - C_{E_i}$$

where: c_i = observed cost for i^{th} quarter

C_{E_i} = calculated cost for i^{th} quarter using predicted cost line equation

d_i = deviation of i^{th} cost point measured from the predicted cost line

The results of these calculations are presented in Table 14.

Table 14

Deviations About The Predicted Cost Line

i	c_i	C_{E_i}	d_i
1	4.510	66.377	-61.867
2	10.573	132.754	-122.181
3	20.833	199.131	-178.298
4	38.299	265.508	-227.209
5	48.554	331.885	-283.331
6	59.140	398.262	-339.122
7	69.733	464.639	-394.906
8	77.609	531.016	-463.407
9	81.081	597.393	-516.312
10	83.224	663.770	-580.371
11	84.399	730.147	-645.748
12	86.253	796.524	-710.271
13	88.256	862.901	-774.645
14	89.322	929.278	-839.956

<u>Calculation of the Variance</u>. After measuring the deviations of observed costs from the predicted cost line, the variance of the deviations was calculated. The variance was determined using the following equation (27:573):

$$S_d^2 = \frac{\sum_{i=1}^{n} d_i^2}{n - 1}$$

where: n = number of quarters

d_i = deviation of i^{th} cost point measured from predicted cost line

S_d^2 = sample variance of the deviations

The result of this calculation was $S_d^2 = 269125.51$. The variance calculation was compared with the variance of the errors using the F-test presented below.

Statistical Test

<u>Statement of the Hypotheses</u>. The statement of the hypotheses in the statistical test was:

Null Hypothesis (H_o): $\sigma_e^2 = \sigma_d^2$

Alternate Hypothesis (H_1): $\sigma_e^2 \neq \sigma_d^2$

As stated, the hypotheses represent a two-tail test comparing variances (16:114).

<u>Computation of Calculated F</u>. The following equation was used to determine the value for calculated F, denoted by

F_c, with 13 degrees of freedom (16:114):

$$F_c(13,13) = \frac{\text{Larger Variance}}{\text{Smaller Variance}}$$

$$= \frac{S_d^2}{S_e^2} = \frac{269125.51}{105.6178} = 2548.1075$$

Statement of the Decision Rule. The following decision rule was used to test the homogeneity of the two variances (16:115).

> If $F_c(13,13)$ is greater than the critical F, denoted F*, then H_o can be rejected.
>
> If $F_c(13,13)$ is less than or equal to F*, then H_o cannot be rejected.

F* is the critical value determined from a book of standard statistical tables.

Determination of F*. F* for 13 degrees of freedom was calculated at the one, five, and ten percent significance level using a book of standard statistical tables (27:621-628). The results of the calculations are presented in Table 15.

Table 15

Critical Values of F

Significance Level	Critical Value (F*)
1%	4.58
5%	3.12
10%	2.58

Decision. Since $F_c(13,13) = 2548.1075$ is greater than F* at the one, five, and ten percent significance levels, H_o could be rejected. The F-test for homogeneity of variances indicated that there was significance between S_e^2 and S_d^2. This result implies that both variances are not estimates of σ^2 (the population variance), and are not sample variances belonging to the same population. Therefore, the research hypothesis of this study can be rejected.

APPENDIX D

COMPARISON WITH THE GLOVER-LENZ STUDY

The methodology used in the Glover-Lenz study formed the basis for the current study. However, the authors of the current study could not confirm the relative entropy value of .686 presented in the Glover-Lenz study as stemming from Figure 14 (p. 104), Table 3 (p.50), Table 6 (p. 95), or Table 8 (p.98) of the Glover-Lenz thesis. These tables and figure are presented in this appendix and consist of the following data:

Figure 17	Glover and Lenz Figure 14 Entropy Computation Input and Output
Table 17	Glover and Lenz Table 3 Entropy Data Collection Results
Table 18	Glover and Lenz Table 8 Summary of Round III Responses to DELPHI Interrogation
Table 20	Glover and Lenz Table 6 Summary of Round II Responses to DELPHI Interrogation

DISCREPANCIES IN GLOVER-LENZ STUDY

The data presented in these tables and figure reportedly formed the basis for calculating relative entropy leading to the subsequent statistical test of the Martin Cost Model which supported their research hypothesis. Errors in the data presentation by Glover and Lenz, apparently typographical, have resulted in the current authors' inability to confirm the specific values presented in the earlier study and presented in Table 16.

Figure 17 reflects the input-output data displayed in the Glover-Lenz Figure 14. The input data was used in their computer program for calculating relative entropy. This computer program is the same one used in the current study and presented in Appendix B. After verifying the accuracy of the program, the authors of the current study found that the input data presented in Glover-Lenz Figure 14 did not produce the output data as presented in that Figure 14. Using their input data, a relative entropy (h) of .70575420 was output utilizing the given computer program. It was found, through repeated cross referencing, that the values for the Unacceptably Poor category of the Radar Cross Section feature and Missile Speed feature were not .2175 and .2250 as reflected in Glover-Lenz Table 3, but actually .2125 and .255 respectively. The FB-111 Interface, Unacceptably Excellent category was .05 in Glover-Lenz Figure 14 and .1375 in Glover-Lenz Table 3.

Table 17 reflects the data presented in Glover-Lenz Table 3. Table 18 presents the arithmetic mean of each feature category or probability outcome category for each area of uncertainty in the SRAM development as presented

Table 16

Relative Entropy Summarization from Glover-Lenz Study (16:53)

$m = n = 19.683$ = number of outcomes

$$H = -\sum_{i=1}^{19.683} p_i \log p_i = 2.9464$$

$H_{max} = \log 19683 = 4.2941$

$$h = \frac{H}{H_{max}} = \frac{2.9464}{4.2941} = 0.686 = \text{relative entropy}$$

Model Final Cost Prediction (16:56,107)

$$C_E = \frac{C_I}{1 - h} = \frac{143.3}{1 - .686} = \$456.4 \text{ million}$$

C_E = estimated final cost; C_I = initial cost estimate (in millions)

C_A = \$439.1 million = actual final cost

F-Test (16:54,58-59)

$$F_c = \frac{S_e^2}{S_d^2} = \frac{812.36}{779.06} = 1.04$$

where 21 quarterly time periods were involved.

Findings (16:115)

$F_c < F^*$ with 20 degrees of freedom at the .01, .05, and .10 level of significance. H_o could not be rejected.

```
.325,.625,.05
.1375,.725,.1375
.475,.475,.05
.2125,.700,.0875
.1375,.825,.0375
.475,.45,.075
.225,.7125,.0625
.255,.7125,.0625
.0875,.825,.0875
```

```
H=         0.68614852E 00
HSUM=      0.29463844E 01
HMAX=      0.42940913E 01
EVNTNO=    0.19683000E 05
PSUM=      0.99999975E 00
```

Figure 17

Entropy Computation Input and Output,
Glover-Lenz Figure 14
(16:104)

Table 17

Entropy Data Collection Results,
Glover-Lenz Table 3
(16:50)

Feature	Unacceptably Poor	Acceptable	Unacceptably Excellent
1	.3250	.6250	.0500
2	.1375	.7250	.1375
3	.4750	.4750	.1375
4	.2175	.7000	.0875
5	.1375	.8250	.0375
6	.4750	.4500	.0750
7	.2250	.7125	.0625
8	.2250	.7125	.0625
9	.0875	.8250	.0875

Table 18

Summary of Round III Responses to
DELPHI Interrogation,
Glover-Lenz Table 8
(16:98)

Feature	Unacceptably Poor	Acceptable	Unacceptably Excellent
1	.2750	.6500	.0750
2	.1875	.7000	.1125
3	.4250	.5000	.0750
4	.2125	.7000	.0875
5	.1375	.8250	.0375
6	.4750	.4500	.0750
7	.2250	.7125	.0625
8	.2250	.7125	.0625
9	.0875	.8250	.0875

in Glover-Lenz Table 8. It was the data from this latter table which was to be input data for calculating relative entropy by way of the computer program (16:101). Aside from discrepancies in input data of Glover-Lenz Figure 14, which should have the same data as their Table 3, the arithmetic means, as presented in the Glover-Lenz Table 3, are discrepant with their Table 8. Figure 14, Table 3, and Table 8 of the Glover-Lenz study should have the same mean value. The mean values of their Table 8 have been reproduced and are reflected in Table 18 of the current study. Their Table 8 represented the third and final round of the DELPHI interrogation and formed the basis for the values in their Table 3 (16:97). The discrepancies between their Table 3 and Table 8 are presented in summary form in Table 19. It should also be noted that the sum of the probabilities for the FB-111 Interface, as presented in their Table 3, is greater than 1.0.

In attempting to determine the origin of the discrepancies in Table 18, the authors of the current study found that the values for discrepancy number one through eight apparently came from Glover-Lenz Table 6 (16:95), Summary of Round II Responses to DELPHI Interrogation, as shown in Table 20. The origin of discrepancy number nine and ten could not be determined.

Although a relative entropy (h) of .686 and an F calculated (F_c) of 1.04 were reported in the Glover-Lenz study as leading to acceptance of the null hypothesis and

Table 19

Discrepancies Between Table 3 and 8 of Glover-Lenz Study

Discrepancy Number	Feature	Probability Category	Table 3 Value	Table 8 Value
1	Rocket Motor Performance	U.P.	.3250	.2750
2		A	.6250	.6500
3		U.E.	.0500	.0750
4	Missile Accuracy	U.P.	.1375	.1875
5		A	.7250	.7000
6		U.E.	.1375	.1125
7	FB-111 Interface	U.P.	.4750	.4250
8		A	.4750	.5000
9		U.E.	.1375	.0750
10	Radar Cross Section	U.P.	.2175	.2125

Probability Category Code:

U.P. = Unacceptably Poor
A = Acceptable
U.E. = Unacceptably Excellent

Table 20

Summary of Averages of Round II Responses
to DELPHI Interrogation,
Glover-Lenz Table 6
(16:96)

Aspect Number	Unacceptably Poor	Acceptable	Unacceptably Excellent
1	.3250	.6250	.0500
2	.1375	.7250	.1375
3	.4750	.4750	.0500
4	.2125	.7000	.0875
5	.1375	.8250	.0375
6	.4125	.5125	.0750
7	.2250	.7125	.0625
8	.2125	.7250	.0625
9	.0875	.8250	.0750

support of their research hypothesis, these values could not be duplicated using the data provided. The discrepancy between each individual probability value was less than .10 and did not appear to represent a gross error. Keeping in mind there were no further data available to verify the validity of Round II and Round III data of the Glover-Lenz study, a range of possible entropy and F_c values were prepared using the referenced tables and figure and are reflected in Table 21. It was necessary, however, to make a correction to the formula for Calculation of Variance of the errors of the observed points (16:109) and for the variance of the deviations (16:112) before continuing the comparison. Table 22 presents the original formula used by Glover and Lenz (16) and the corrected formula (27:573) necessary for the computation of the variances. If it can be assumed that the probability assessments of the participants for the second and third round of the DELPHI interrogations are either correct as presented in the Glover-Lenz study or contain very few and only slight differences from the actual data that was collected (similar to those differences cited in Appendix D), then each table and figure that is pertinent to relative entropy and subsequent test calculations may be considered separately and comparisons made to gain insight into whether or not the finding of the Glover-Lenz study is accurate. Such assumptions were made by the authors of the current study. Each of three tables and a figure that were deemed as being

Table 21

F_c Data Calculations from Glover-Lenz Data Sources

Data Sources	Values
Round II Data	$\sum d_i^2 = 76664.933$
	$\bar{d} = 53.682$
	$n = 21$
	$s_d^2 = 807.4017$
	$s_e^2 = 812.36$
	$F_c = s_d^2/s_e^2 = .9938964$
Round III Data	$\sum d_i^2 = 45015.53$
	$\bar{d} = 37.314047$
	$n = 21$
	$s_d^2 = 788.8215$
	$s_e^2 = 812.36$
	$F_c = s_d^2/s_e^2 = .9710245$
Table 3 Data	$\sum d_i^2 = 44027.73$
	$\bar{d} = 16.209523$
	$n = 21$
	$s_d^2 = 1925.5004$
	$s_e^2 = 812.36$
	$F_c = s_d^2/s_e^2 = 2.370255$

Table 21 (continued)

Data Sources	Values
Figure 14 Data	$\sum d_i^2 = 31428.699$
	$\bar{d} = 25.671285$
	$n = 21$
	$S_d^2 = 879.46935$
	$S_e^2 = 812.36$
	$F_c = S_d^2/S_e^2 = 1.0826103$

Table 22

Variance Formulae Corrections

Original Formulae	Corrected Formulae
$s_e^2 = \dfrac{\sum_{i=1}^{n} e_i^2 - n\bar{e}}{n-1}$	$s_e^2 = \dfrac{\sum_{i=1}^{n} e_i^2 - n\bar{e}^2}{n-1}$
$s_d^2 = \dfrac{\sum_{i=1}^{n} d_i^2 - n\bar{d}}{n-1}$	$s_d^2 = \dfrac{\sum_{i=1}^{n} d_i^2}{n-1}$

directly relevant to entropy and statistical test calculations was applied separately in making those calculations. The results are reflected in Table 21 of Appendix D. In only one instance was the null hypothesis rejected. That rejection occurred at the .10 level of significance for the data representing Table 3, "Entropy Data Collection Results," or the calculated arithmetic means of the aspect feature probability outcomes (16:50). Thus, the authors of the current study believe that, regardless of the apparent typographical errors in the data as presented in the Glover-Lenz study, Glover and Lenz were probably correct in their finding of nonrejection of the null and, thereby, the research hypothesis based upon their method of statistical testing.

APPLICABILITY OF THE STATISTICAL TEST

Aside from any possible doubts as to the adequacy of the sample sizes and the assumptions of normality, the assumed independence of the variable time (t_i), error (e_i), deviation (d_i), and the actual observed cost (c_i) from previous outcomes as reflected by prior dependent variables or cost observations, $\sum_{i=1}^{x} c_i - 1$, can be called into question in both studies (35:247-257,282,461-463,469-474, 485-493; 33:481-491).

Both within the Glover-Lenz study (16:36,65) and in this appendix, the validity of the assumption of linear cost has been addressed. However, in regards to the relationship of this assumption to the appropriateness of the statistical test used, Glover and Lenz go on to state the following (16:65):

> The assumption of linear cost relative to time may be criticized as unrealistic, and perhaps as invalidating any results due to possible intercorrelation of cost observations with respect to subsequent time points. However, the random variables of the statistical test were the errors of the actual cost from the least-squares fitted line and the deviations from the projected straight line from the origin to the Martin Cost Model estimate of final cost. As such, the test takes the form of assessing whether the two projections could have come from the same family of possible linear cost estimates for the SRAM program. Such a test is internally consistent with the assumptions of the study. Note that linearity of cost appears to be a typical assumption in capital budgeting. Weapon system acquisition decisions are conceptually similar to the capital budgeting decision.

Based upon a further review of the literature, the authors of the current study have come to believe that the assumption of independence for the above cited variables, as implied by both the statistical testing method employed and the above statement from the Glover-Lenz study, is invalid. Since the dependent variable is the cumulative cost or $\sum_{i=1}^{x} c_i$ for a given time point t_i, where $i = 1, \ldots, x$, then both a trend of increasing cost and random-tracking patterns should occur over time. Thus, at least under the least-squares method of fitting a line through the observed cost data, the necessary assumptions of independence under simple, linear regression techniques is inappropriate for these two studies (35:268,282). Further, from a logical standpoint it would also appear that each d_i should be independent if the variances (S_e^2 and S_d^2) based upon e_i and d_i are to be compared on an equal footing. Similar to the case of e_i, each d_i does not appear to be independent since $d_i = c_i - C_{E_i}$ where $c_i = \sum_{i=1}^{x} c_i$ and

$$C_{E_i} = \sum_{i=1}^{x} C_{E_i}$$

at $t_i = x$ (see Appendix C, Table 14). Therefore, it appears that some form of time series analysis rather than simple linear regression techniques should have been employed so that the relationship between the variables and the various patterns of dependency could be differentiated for purposes of analysis and testing.

The appropriateness of using the actual, individual cumulative cost values as the basis upon which to determine the accuracy of the predicted final cost can also be called into question from the standpoint of the basic purpose of these studies. These studies were designed to analyze and test the ability of the model to predict, with accuracy, the final cost of a development program. Therefore, the emphasis should be upon one point in time, T_N. The values of C_I and IE that are used to make that prediction originated at time T_O. If the model is to be used in actually identifying and in controlling potential and actual areas of cost growth, then, as described in Chapter II, the prediction would be updated as the program progresses based upon the measurement of IE and the incorporation of any changes in C_I at time period T_i. In the case of the current study, which reflects somewhat the same situation as depicted in Figure 9, Chapter II, the predicted cost of the program from the origin, T_O, would immediately identify the program as being potentially out of control. Such identification would have resulted in a reassessment of the prediction and an upgrading of IE and/or C_I through the subsequent research efforts to determine potential areas of cost growth and/or alternative outcomes not before considered.

APPENDIX E

ENTROPY OUTPUT DATA COMPARISON

Some consideration was given to a close examination and comparison of the participant probability assignment. In Chapter II and Appendix B, it was explained that participant 4 was removed from the study for specific reasons. Though removed, the areas of uncertainty participant 4 contributed were retained under the assumption they would not have an adverse affect on the study. In comparing the output in Table 23 with and without the data provided by participant number 4, we find little overall difference in the value calculated for relative entropy. In fact, when the aspects of uncertainty contributed by participant number 4 are removed, the value for total relative entropy increased by only .011 from .910 (with) to .921 (without).

In assigning probability valu·· to the DELPHI procedure questions, there were some completely opposite responses between two participants. Table 23 represents an attempt at combining the responses of the participants to reduce the "extreme effect" of probability assignment. The union of the responses of participant number 1 and participant number 3 reduce this "effect" and contribute a

Table 23

Entropy Data Comparison

Participants	Relative Entropy A^1	Relative Entropy B^2
1 & 2	.902	.949
2 & 3	.919	.925
1 & 3	.726	.732
1, 2 & 3	.910	.921

A^1 = relative entropy values to include areas of uncertainty from participant number 4

B^2 = relative entropy values not to include areas of uncertainty from participant number 4 lower, more desirable relative entropy value and, in turn, a higher value for informational efficacy.

The initial final development program cost estimate, C_I, was $83.635 million and the actual final cost estimate, C_A, was $89.322 million. Using the Martin Cost Model calculations, substituting C_A for C_E, and a C_I of $83.635 million, a relative entropy value of .06366 would be required to produce a final development cost of $89.322 million. To produce such results would require a probability assignment of approximately .00749 for one of the outcomes of each of the 12 aspects in the current study.

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